US Army Corps of Engineers
Los Angeles District

Santa Cruz River, Paseo de las Iglesias
Pima County, Arizona

Final Feasibility Report
and
Environmental Impact Statement

APPENDIX A

HYDROLOGIC INVESTIGATION

July 2005

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PREFACE

Hydrologic analysis for the Paseo de Las Iglesias Feasibility Study included both the mainstem Santa Cruz River and its tributaries within the study area. The study area extended from Los Reales Road on the south to Congress Street on the north. Peak discharges for the Santa Cruz River mainstem (Santa Cruz River at Tucson) had recently been updated by the U.S. Army Corps of Engineers, Los Angeles District, within a separate study. Peak discharges for the Santa Cruz River tributaries were provided by the the Pima County Department of Transportation & Flood Control District. This report presents summarizes the surface water hydrology for the study area, and the hydrologic "base conditions" or "without project" conditions used to describe and quantify the potential flooding problem in the study area resulting from runoff to the Santa Cruz River and its tributaries. Included in this report are discharge-frequency values provided by Pima County and an evaluation of those discharges performed by the Los Angeles District as well as additional tributary discharges estimated by the Los Angeles District based upon the results of the evaluation and the information provided by Pima County.

Supplemental Hydrology Report

PASEO DE LAS IGLESIAS

FEASIBILITY STUDY

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1 INTRODUCTION

1.1 STUDY AREA: The Paseo de Las Iglesias Feasibility Study encompasses the Santa Cruz River bounded on the upstream side by Los Reales Road and on the downstream side by Congress Street. In addition the study area includes tributary runoff to the Santa Cruz River from the Old West and New West Branches, as well as other local intervening drainage areas.

1.2 PURPOSE: The hydrologic information presented in this report will be used to support sedimentation analyses, develop overflow mapping, and assist in economic evaluation of without project conditions.

1.3 SCOPE: Hydrologic information presented in this report is taken from previously published reports by the Los Angeles District, U.S. Army Corps of Engineers (LAD), and from information provided by the Pima County Department of Transportation & Flood Control District (referred to hereinafter as PCFCD). This report includes without project discharge-frequency values for the mainstem Santa Cruz River, the Old West Branch and the New West Branch of the Santa Cruz River, and tributary washes which deliver local runoff to the Santa Cruz River within the study area. The discharges for the mainstem were developed by the LAD for the location near Congress Street in Tucson, AZ[1], as a component of the Santa Cruz River Watershed Management Study. Discharges for the Old and New West branches and other tributaries were multi-source and provided by PCFCD except for locations noted herein . In addition to discharge-frequency values for the mainstem Santa Cruz River, synthetic flood hydrographs, developed from available volume-frequency information, are included in this report. This report documents several aspects involved in generating the hydrologic information described above.

1.3.1 Evaluation of discharge-frequency values provided by PCFCD for tributaries of the Santa Cruz River.

1.3.2 Extension of the discharge-frequency values for New West Branch Wash provided by PCFCD to include the 500-year peak flow rates (0.2% chance of exceedance during any given year), and estimation of n-year peak flow rates for the Los Reales Improvement District.

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[1] Congress Street is at the downstream end of the study area. Discharges in the mainstem Santa Cruz River do not vary significantly within the study area.

1.3.3 Development of Synthetic Hydrographs (Balanced Hydrographs) for use in sedimentation analysis of the Santa Cruz River within the study area. Peak discharge-frequency values for flood control analysis of the Santa Cruz River presented in this report were developed in reference 2.3, as mentioned in the previous paragraph.

1.3.4 Development of Risk/Uncertainty information for economic evaluation of base conditions and formulation/evaluation of project flood control alternatives.

2 REFERENCES AND ASSOCIATED REPORTS

Reports pertinent to the hydrology for the Paseo de Las Iglesias Feasibility Study are included below:

2.1 EL RIO ANTIGUO, RILLITO RIVER ENVIRONMENTAL RESTORATION, DOCUMENTATION FOR HYDROLOGIC STUDIES, prepared by Pima County Department of Transportation and Flood Control District, Flood Control Engineering Division, for the U.S. Army Corps of Engineers, Los Angeles District, March 2002.

2.2 SANTA CRUZ RIVER, PASEO DE LAS IGLESIAS, PIMA COUNTY, ARIZONA, FEASIBILITY STUDY, HYDROLOGY REPORT, Pima County Flood Control District, November 2001.

2.3 GILA RIVER, SANTA CRUZ RIVER WATERSHED PIMA COUNTY FINAL FEASIBILITY STUDY, APPENDIX E-1, Los Angeles District, U.S. Army Corps of Engineers, August 2001.

2.4 RISK-BASED ANALYSIS OF FLOOD DAMAGE REDUCTION STUDIES, DRAFT, EM 1110-2-1619, US Army Corps of Engineers, 1 March 1996.

2.5 REQUEST FOR A LETTER OF MAP REVISION FOR THE LOS REALES IMPROVEMENT DISTRICT LOCATED IN PIMA COUNTY, ARIZONA, AND IN THE CITY OF TUCSON, ARIZONA, prepared by Arroyo Engineering, Inc., December 1994.

2.6 METHODS FOR ESTIMATING MAGNITUDE AND FREQUENCY OF FLOODS IN THE SOUTHWESTERN UNITED STATES, U.S. Geological Survey Open File Report 93-419, 1994.

2.7 FLOOD DAMAGE REPORT, STATE OF ARIZONA, FLOODS OF 1993, US Army Corps of Engineers, Los Angeles District, August 1994.

2.8 SANTA CRUZ RIVER HYDROLOGIC DOCUMENTATION FOR FEASIBILITY STUDIES, LOWER SANTA CRUZ RIVER FLOOD CONTROL STUDY, PINAL COUNTY ARIZONA, Los Angeles District, U.S. Army Corps of Engineers, July 1990.

2.9 METHODS FOR ESTIMATING MAGNITUDE AND FREQUENCY OF FLOODS IN THE ARIZONA, by R.H. Roeske, United States Geological Survey Water Resources Division, Report: ADOT-RS-15[121] Final Report, September 1978.

3 DRAINAGE AREA DESCRIPTION

The Santa Cruz River is a tributary to the Gila River, which in turn is a tributary to the Colorado River. The Gila River Basin comprises 58,200 mi^2 in New Mexico, Arizona, and Mexico. The Santa Cruz River Basin consists of approximately 8200 mi^2 in southern Arizona and 400 mi^2 in Mexico. A map delineating the Santa Cruz River drainage basin from its headwaters downstream into Pinal County, and its location within the State of Arizona is provided in Plate E1-1.

The Santa Cruz River rises in the Patagonia and Huachuca Mountains in southern Arizona near the town of Lochiel, flows south across the international boundary and makes a 35 mile long loop westward through Sonora, Mexico and then turns northward and reenters the United States about 6 miles east of Nogales. The channel continues north to Tucson, then turns northwestward and flows 42 miles to Greene Canal. From here, most of the flow is diverted to Greene Canal and continues through several distributary channels about 75 miles towards Laveen at the confluence with the Gila River (about 10 miles upstream of the Salt River confluence and about 80 miles upstream of Painted Rock Dam on the Gila River).

The Santa Cruz River basin is characterized by a wide valley broken by several broad, low hills and mountains. The basin area has a maximum length of approximately 175 miles and is about 80 miles wide at its widest point. Stream gradients in the basin range from about 29 feet per mile near Lochiel to 18.5 feet per mile at Tucson to 8 feet per mile at the Gila River confluence.

The Santa Cruz River and principle tributaries are mostly ephemeral, being dry for long periods of time. Flows in the river are a result of direct or upstream precipitation or irrigation tailwater in the basin. For a short distance downstream of Tucson, the river conveys a perennial flow of sewage effluent from a sewage treatment plant.

Analysis of the basin indicates the confluence with Los Robles Wash marks a change in the character of the runoff; just upstream the Los Robles Wash system (Altar Wash, Brawley Wash, drainage area = 1390 mi^2) enters the Santa Cruz River and is the last major source of uncontrolled runoff from mountainous terrain.

From the headwaters to the confluence with Los Robles Wash, the Santa Cruz River is a "gaining" river, meaning discharge generally increases with drainage area. Downstream from the confluence to the mouth (at the confluence with the Gila River), the flood plain flattens and broadens out in the area known as the "Santa Cruz Flats" and becomes a "losing" river. In this reach flood flows are dramatically attenuated such that discharge decreases with an increase in drainage area. Flows originating in the upper reaches of the Santa Cruz River rarely reach the Gila River; when they do reach the Gila River, they are usually augmented by tributary flows originating in the lower part of the basin. The streambed materials are extremely permeable especially from Cortaro to Laveen, resulting in high rates of infiltration.

Total rainfall and the areal distribution of rainfall are affected by relative elevations of the various parts of the drainage area. Elevations in the basin range from 9432 feet NGVD at Mount Wrightson in the Santa Rita Mountains to about 1000 feet NGVD at the Gila River confluence. The crest-stage gage at Congress Street in Tucson was located at datum 2317.82 feet, National Geodetic Vertical Datum of 1929 (it has since been moved about 300 feet downstream).

Valleys occupy almost 70% of the area and the primary land use in the basin is irrigation agriculture, both on Indian as well as private land. Agriculture is limited by the available water supplies. Irrigation water is supplied principally from groundwater sources, which are recharged by precipitation over the area. The growing season in the basin is fairly long and a wide variety of crops are produced. Much of the flood plain contains soil suitable for growing such crops as cotton (the principle agriculture crop), grains, and pecans where irrigation water is available.

Vegetation in the Santa Cruz River basin is sparse and consists of typical desert cover of creosote bush, sagebrush, paloverde, desert shrubs, and cacti in the lower elevations, assorted grasses in the upper valleys, and fir, pine, juniper, chaparral, and pinon forests in the higher mountains. Along the stream channels thicker and denser vegetation made up of mesquite forests, cottonwood and willow trees and various reeds and grasses can be found.

Soils in the Santa Cruz River watershed are extremely varied. The mountains consist of weathered native rock, while the valley floors contain unconsolidated gravels, sands, silts, and the clays derived from these rocks. The soils of the mountain area are shallow and stony with occasional rock outcrops. Desert and semi-desert soils occur in the hills and valleys. The valley surface soils generally range from fine silty clays to clay and are fairly deep. The stony or gravelly alluvial fans, formed by coarse material shed from the mountains, are underlain by subsoil material that is highly calcareous and more or less firmly cemented.

4 PRECIPITATION AND RUNOFF

4.1 GENERAL. The climate in the Santa Cruz River Basin is typically desert in character with short, mild winters and long, hot summers. High diurnal temperature variations are characteristic of the region. Temperature extremes range from about 12° Fahrenheit in the winter to 122° Fahrenheit in the summer. The prevailing winds are from the east and are usually light, although severe windstorms occur at rare intervals.

Mean annual precipitation ranges from 11 inches in the valleys to over 37 inches at elevations greater than 8000 feet NGVD. Studies conducted in the Tucson vicinity show an extremely low percentage (about 1%) of the rainfall appears as runoff, generally evaporating or returning to groundwater. The mean annual precipitation at the station Tucson NWSO (National Weather Service Office) for the period 1894 - 2000 is 11.3 inches. At the station Tucson 17 NW, the mean annual precipitation is 12.8 inches for the period from 1982 - 2000. The latter station is at an elevation of 2561 feet above mean sea level, or 83 feet higher than the NWSO station.

Annual precipitation at the NWSO station has varied from a maximum of 24.2 inches (1905[2]) to a minimum of 11.3 inches (1924). The maximum monthly precipitation occurred in July of 1984 (7.56 inches) while the minimum total (0.00 inches) has occurred in numerous months/years. The wettest months of the year on average are August and July (2.14 inches and 2.05 inches, respectively), while the wettest winter month is December (1.0 inches).

Precipitation occurs in two distinct seasons of the year; summer (late June, July, August, September, and into October; and winter - December, January, February, and March.

4.2 MONSOON SEASON. Summer rains in the form of thunderstorms originating in moist air that flows into Arizona from the Gulf of Mexico generally occur in middle to late afternoon and are usually of local extent. Approximately 80% of the thunderstorms over the basin occur in the summer months. Floods associated with summer thunderstorms can be extremely flashy (up to 3 hours) and are of short duration.

[2] Note: February, March, April, and November of 1905 were the wettest individual February, March, April, and November months during the entire period of record.

4.3 CYCLONIC SEASON. Some general summer storms do occur during the period July through September. They are associated with an influx of tropical maritime air originating over the Gulf of Mexico or the south Pacific Ocean and entering the area from a southeast or a southwest direction. Usually the influx of tropical air is caused by the circulation about a high-pressure area centered in the southeastern United States, but occasionally is caused by remnants of a tropical hurricane. There is often relatively heavy precipitation for periods of up to 24 hours and showers may continue intermittently for as long as 3 days. Flooding commonly covers a wide area with durations of about 24 hours.

4.4 FRONTAL SEASON. Winter precipitation is normally associated with the passage of cyclonic storm centers originating in the Pacific Ocean, which commonly are a result of interaction between polar Pacific and tropical Pacific air masses. Some snow falls at the higher elevations, but the effect on flood flows is negligible. Individual storms usually are of several days' duration and wide areal extent, with slow and steady intensity. Winter floods from these storms are of longer duration with lower flood crests.

4.5 RECORDED DATA. Currently the United States Geological Survey (USGS) operates streamflow recording gages on the Santa Cruz River at the locations listed in the following table:

Table 1: USGS Streamgage Information for Santa Cruz River

USGS Streamgage Number	Location	Drainage Area (mi^2)	Period of Record	
			Systematic	Historic
09480000	Santa Cruz River nr. Lochiel	82.2	1949-present	1926-present
09480500	Santa Cruz River near Nogales	533	1930-present	1892-present
09482000	Santa Cruz River at Continental	1662	1940-present	1892-present
09482500	Santa Cruz River at Tucson	2222	1915-1981, 1984-present	1892-present
09486500	Santa Cruz River at Cortaro	3503	1940-1984, 1990-present	1914-present
09489000	Santa Cruz River near Laveen	8581[a]	1940-present	1940-present

[a] 1780 mi^2 is controlled by Tat Momolikot Dam

[Note: Locations of pertinent stream gages are included on the accompanying maps on the following page.]

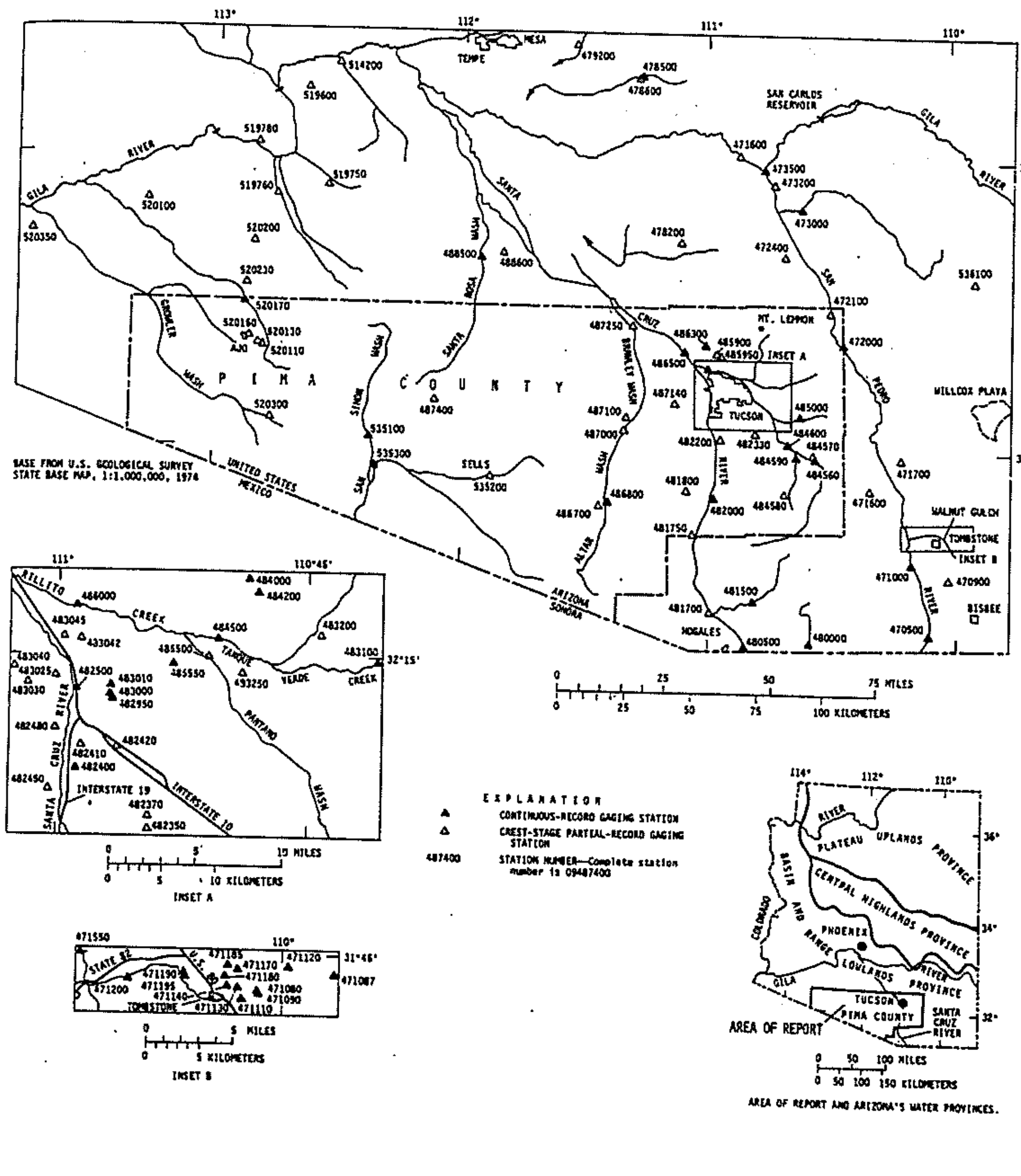

Figure 1 Locations of Stream Gages

5 HISTORIC STORMS AND FLOODS

Available streamflow records, most commonly collected by the USGS, indicate significant floods occurred in the Santa Cruz Basin in 1887, 1926, 1945, 1961, 1962, 1964, 1965, 1967, 1977, 1983, 1991, 1993, and 1996 The largest flood of record for most of the basin occurred in October of 1983. Following is a historical account of some of the flooding and precipitation in the Santa Cruz River basin.

5.1 SEPTEMBER 1887. The Santa Cruz River and Rillito Creek experienced heavy freshets from the 9th to the 12th which destroyed bridges over Rillito Creek and several miles of railroad tracks near Pantano. Water stood "two-miles wide" in the valley north of Tucson. A fifty-foot-high railway embankment near Dragoon was washed out for eight miles.

5.2 FEBRUARY 1890. A general rainstorm covered the area for three days or more with little let-up. The Salt, Gila, Colorado, and Santa Cruz Rivers all overflowed their banks. Farmlands, as well as livestock, were washed away and people all over were stranded.

5.3 AUTUMN 1891. A large cloudburst in the mountains caused flooding along the Santa Cruz River. The river overflowed through agriculture land and washed away crops, animals, and structures. Within a short period of time the river was completely dry.

5.4 DECEMBER 1914. The month of December was generally wet throughout Arizona, probably as an indirect result of low-latitude north Pacific Ocean storms spawned by El Nino conditions. It was the storm series of December 17-24 that produced flooding in southeastern Arizona. Below Marana and Cortaro, railroad tracks were inundated below 4 feet of water and 25 miles of track was washed out. A flood peak of 15,000 cfs occurred on the Santa Cruz River at Tucson (2222 mi^2) on the 23rd, while on the same day the peak observed at the Rillito Creek gage (918 mi^2) was 17,000 cfs. December 1905 was the wettest “winter” month in history at the Tucson NWSO station (5.85 inches).

5.5 SEPTEMBER 1926. One of the most damaging rainstorms over central and southeastern Arizona occurred on the 26th and 27th of this month. Precipitation durations of up to 48 hours were recorded as the storm ranged as far south as central Mexico and as far east as El Paso, Texas. The Arizona cities of Thatcher, Nogales, Douglas, and Safford all received extensive flood damages. A flood peak of 11,400 cfs occurred on the Santa Cruz River at Tucson on the 28th.

5.6 SEPTEMBER 1929. The middle and latter part of the month brought a scattering of relatively heavy thunderstorms to many parts of Arizona. Perhaps aided by favorable overall atmospheric conditions associated with a minor El Nino in the eastern Pacific, there was a deep flow of moist tropical air into Arizona from the 15th to the 25th. Tucson measured 3.40 inches of precipitation for the period between the 22nd and 24th, including 1.39 inches on the 23rd and 2.00 inches on the 24th. Rillito Creek experienced the second largest peak of record, 24,000 cfs, on the 23rd; the Santa Cruz River peaked at 10,400 cfs on the 24th at Tucson.

5.7 AUGUST 1935. Above normal rainfall fell in practically all sections of the state resulting from a moist flow of air from out of the south augmented by a tropical storm that hit the coast of southern California. In Santa Marguerita, 4.10 inches occurred in about an hour and a half on the 22nd and a total of 9.09 inches fell during the month. The heavy rains resulted in numerous flash floods in ordinarily dry washes which caused considerable loss of life and property. On the 31st, flood waters overwhelmed sections of the Rillito Valley and significant damage occurred at other localities between Tucson and Nogales. This storm produced flood peaks of 13,400 cfs and 10,300 cfs on Rillito Creek and the Santa Cruz River at Tucson, respectively. August 1935 was the wettest August recorded at the Tucson NWSO station in history (5.610 inches).

5.8 DECEMBER 1940. The year was one of strong El Nino conditions in the Pacific Ocean. The last three days of December climaxed a wet month with moderately heavy storms all over Arizona. Large flows on Rillito Creek (with a peak of 9900 cfs) were primarily responsible for the 7800 cfs peak observed on the Santa Cruz River at Cortaro (3503 mi^2).

5.9 AUGUST 1945. A storm of cloudburst proportions occurred over ordinarily dry washes in Pima County causing flood waters which rushed downstream and tore a fifteen-foot gap in a bridge on the highway four miles south of Tucson. Four automobiles plunged into the torrent and ten people drowned. The Santa Cruz River had estimated peaks of 7820 cfs at Continental (1662 mi^2) on the 9th, 14,000 cfs at Cortaro (3503 mi^2) on the 10th, 10,800 cfs at Tucson (2222 mi^2) on the 10th, and 1200 cfs near Laveen (8581 mi^2) on the 11th. Rillito Creek peaked at 7000 cfs on the 10th.

5.10 AUGUST 1961. On August 22, about 9:00 PM, over two inches of rain fell in one hour in the Tucson area. The heavy runoff produced by the storm caused severe damage to city streets and county roads along with damage to private property. This storm produced a peak discharge of 16,600 cfs, on the Santa Cruz River at Tucson.

5.11 SEPTEMBER 1962. Tropical storm "Claudia" moved onshore approximately 300 miles southwest of the southern Arizona border near Cedros Island, Baja California late in the evening of the 22nd. The path of the storm was generally northeastward. Five to seven inches of precipitation fell over the headwater areas of Santa Rosa, Jackrabbit, and Brawley Washes, with the heaviest rain falling during the night of the 25th and most of the 26th. Precipitation diminished to about 1 inch in the Vaiva Vo area downstream. The duration of the storm was about 14 to 15 hours and the highest recorded precipitation amount (5.95 in.) was observed at the Arizona-Sonora Museum, about 12 miles west of Tucson. Depths up to 7 inches were estimated for other locations. The major damage area from the flooding extended approximately 100 miles along the Santa Cruz River and tributaries and attained a maximum width of about 8 miles in the area south of Stanfield, where floodwaters from the Santa Cruz River merge with Santa Rosa and Greene Washes. Flow in the channels reached depths of 20 feet with 4 to 5 feet waves. The overflow depths varied from less than one foot to over six feet in the flood plain. Agricultural damages of about $8 million included losses to crops, principally cotton, which was in the early picking stage. Structural damages to levees, dikes, and spreader dams accounted for another $1 million. Road damage was very severe throughout the flooded area. Damages in Pima and Pinal Counties were in excess of $11 million. Santa Rosa Wash had an estimated peak discharge of 53,100 cfs near Vaiva Vo (1782 mi^2). The Santa Cruz River near Laveen peaked at 9200 cfs and Los Robles Wash near Marana (1170 mi^2) had an estimated peak of 32,600 cfs. Estimates for ungaged locations include Sells Wash at Sells (17,200 cfs) and Greene Wash near Eloy (24,100 cfs).

5.12 SEPTEMBER 1964. The storm was caused by an influx of warm, moist, unstable air from hurricane "Tillie". The period of the most intense rainfall occurred during the late hours of the 9th and early morning hours of the 10th, when a cold front moved across southeastern Arizona from the north. The greatest observed rainfall, 6.75 inches, occurred at two locations, the A.K. Mayer Ranch in the Catalina Mountain foothills and at a point west of Sahuarita. The widespread showers and thunderstorm activity that occurred during the period 5-8 September over the upper Santa Cruz River basin produced favorable runoff conditions for this storm. Estimates of peak discharges on the Santa Cruz River include: 2320 cfs near Lochiel (82 mi^2), 1900 cfs near Nogales (533 mi^2), 14,000 cfs at Continental (1662 mi^2), 14,300 cfs at Tucson (2222 mi^2), 15900 cfs at Cortaro (3503 mi^2), and 1340 cfs near Laveen (8581 mi^2). Rillito Creek (918 mi^2) had an estimated peak of 9400 cfs.

5.13 DECEMBER 1965. During the month of December, precipitation was above normal in all sections of the state, but heaviest totals were reported in the mountains with another band of unusually heavy totals running southward through eastern Pinal and Pima Counties. On the 23rd, additional precipitation caused flooding in the southern part of the state along the Santa Cruz River. Damage to roads, utilities, farmlands, crops, livestock, homes, and automobiles was widespread over most of southern Arizona. In Pima and Pinal Counties several hundred acres of cotton and grain land along the Santa Cruz River were flooded, and Rillito Creek ruptured sewage lines, contaminating a number of wells in the Tucson area. The Santa Cruz River had estimated peaks of 5990 cfs at Continental on the 23rd, 16,800 cfs at Cortaro on the 22nd, and 2940 cfs near Laveen on the 26th. Also peaking on the 22nd were Tanque Verde Creek with a peak of 2760 cfs, Rillito Creek with a peak of 12,000 cfs, and Rincon Creek with a peak of 3100 cfs.

5.14 DECEMBER 1967. From the 12th through the 20th, one of the most severe snowstorms in the history of Arizona occurred at higher elevations over much of the state. From a meteorological standpoint, there were actually two main storms, following so close together they were mistaken as one storm. During this nine-day period, some of the heaviest snow in the climatological history of the state brought widespread damage to Arizona. The peak discharge on Greene Canal below Eloy was 10,000 cfs. On Greene Wash, above the Santa

Rosa Wash confluence, near the town of Chuichu the peak was 7200 cfs, and on the Santa Cruz River near Laveen the peak was measured at 2940 cfs.

5.15 SEPTEMBER 1970. Tropical storm Norma, located in the Pacific Ocean below Baja California, initiated a flow of moist air over the Gulf of California toward the desert southwest on the afternoon of the 1st. This heavy rainfall caused rapid runoff that washed out roads and several bridges near Tucson and flooded homes. Flooding occurred in Altar and Brawley Washes, northwest of Cortaro, primarily due to heavy rainfall near the border town of Sasabe. Sabino Creek, which drains the Catalina Mountains near Tucson, experienced a record peak stream flow of 7730 cfs. Agricultural damage was light as was loss of livestock and damage to field crops.

5.16 AUGUST 1971. An unusually well-developed summer monsoon brought abundant moist air into the state on a consistent basis throughout the month. This moisture caused extensive thundershowers over the state, producing monthly rainfall totals which were above normal in many sections. The monthly totals at some stations were great enough to set new records for the month.

5.17 OCTOBER 1977. One of the most notable weather events of 1977 occurred during the first part of October. Several days of heavy rains caused severe flooding on the Santa Cruz and San Pedro Rivers (and other tributaries) in the southern portions of the state. The flooding produced severe damage to crops, goods, livestock, water supplies, and property. The heavy rains were due to tropical storm Heather which moved toward Baja California on the 5th as a hurricane. On the 6th at noon, its classification was downgraded to a tropical depression. Although almost all of Arizona received some precipitation, the most notable aspect of the storm was the persistently localized and intense rainfall in extreme southern portions of the state and into Mexico. Nogales officially reported 8.3 inches, but unofficial reports of up to 12 inches were received in various parts of that community. Recorded peak discharges for the October 1977 flood include: Santa Cruz River at Continental, 26,500 cfs; Santa Cruz River at Tucson, 23,700 cfs; Santa Cruz at Cortaro, 23,000 cfs; Los Robles Wash near Marana, 2400 cfs; Brawley Wash near Three Points, 7300 cfs; Santa Cruz River at Greene Canal, 5200 cfs (5180 mi^2; Santa Cruz River above Santa Rosa Wash near Stanfield, 4700 cfs; drainage area not measured), and Santa Cruz River near Laveen, 2010 cfs.

5.18 DECEMBER 1978. The storm originated when a large low-pressure trough dropped southward off the California coast from out of the Gulf of Alaska. As circulation around the low plunged deep into the tropics, a very deep and intense current of tropical moisture streamed northward into Arizona from off a very active equatorial zone. On the Santa Cruz River, upstream from Rillito Creek, the flood was the 3rd highest winter in the period that began in 1905 and was exceeded only by the peaks of December 1914 and December 1967. All of these were later exceeded by the January 1993 flood. Flow from Rillito Creek combined with flows from a few minor tributaries to produce a peak of 18,800 cfs at the Santa Cruz River at Cortaro. A second crest of 18,200 cfs occurred when the peak passing

Tucson was superimposed on the recession hydrograph for Rillito Creek. The Santa Cruz River had peak discharges of 7,000 cfs at Continental (1662 mi^2), 13,500 cfs at Tucson (2222 mi^2), and 4120 cfs near Laveen (8581 mi^2). Rillito Creek near Tucson (918 mi^2) was measured at 16,400 cfs, and Canada Del Oro (250 mi^2) had a estimated peak of 1380 cfs. Smaller tributary peaks include 12,700 cfs for Tanque Verde Creek (219 mi^2), 1530 for Pantano Wash (599 mi^2), 1400 cfs for Bear Creek (16.3 mi^2), 7400 cfs for Sabino Creek (35.5 mi^2), 334 for Tucson Arroyo (8.2 mi^2), and 234 cfs for Ventana Canyon Wash (6.46 mi^2).

5.19 OCTOBER 1983. Tropical storm Octave off the coast of Baja California, was the main cause of large floods (in numerous cases the period-of-record peak flow) on the San Francisco, Gila, San Pedro, Santa Cruz Rivers, and other smaller streams. The long period of rainfall from September 27 to October 3 was the result of the interaction of a high-altitude low-pressure trough and a persistent supply of moist tropical air that was vastly increased on September 30 by the arrival of moisture associated with tropical storm Octave. As much as 11 inches of precipitation fell during the 7-day storm period. Rainfall during the storm period contributed to the highest annual precipitation and the highest September-October seasonal precipitation at many of the precipitation stations in the area. The highest recorded precipitation in the Santa Cruz Basin was measured at an elevation of 7,000 feet in the Santa Catalina Mountains, just north of Tucson. Before the storm period began, rainfall had been above normal in most parts of the area, soil conditions being mostly saturated. Flood flows in the Santa Cruz River Basin originated mostly between Nogales and Cortaro, with large volumes of water breaking out of the channel and spreading out over a broad area, especially downstream from Red Rock (refer to Plate 1 for location of Red Rock). The flood on the Santa Cruz River was the largest on record from Continental to the junction with the Gila River. At Interstate 8, the inundation area was more than 8 miles wide. Large channel changes took place on many streams. Total damages were estimated to be $226.5 million. The following peaks were recorded or estimated on the Santa Cruz River: 3880 ft^3/s near Lochiel, 16,200 ft^3/s near Nogales, 45,000 ft^3/s at Continental, 52,700 ft^3/s at Tucson, 65,000 ft^3/s at Cortaro, and 33,000 ft^3/s near Laveen. Other peak discharges in the Santa Cruz River basin included 29,700 ft^3/s on Rillito Creek (the greatest flow of record), 12,500 ft^3/s on Los Robles Wash, 19,100 ft^3/s on Brawley Wash, 6600 ft^3/s on Canada Del Oro, and 1890 ft^3/s on Santa Rosa Wash, (**note**: this is outflow from Tat Momolikot Dam). October 1983 was the wettest October recorded at the Tucson NWSO station (5.78 inches) in history.

5.20 JANUARY 1993. Heavy rains of January 1993 followed an above average rainfall season in 1991-1992, in which above normal precipitation was measured at many stations. January 1993 was the wettest January recorded at the Tucson NWSO station (5.58 inches) in history. This followed December 1992, in which 3.60 inches of precipitation were recorded at that station, nearly 3 times the monthly average. A series of disturbances to the moist flow of subtropical air resulted in widespread storms throughout the state of Arizona. The single-day maximum recorded value at Tucson NWSO was 1.50 inches on the 8^{th} and a combined 2-day total of 2.14 inches on the 7^{th} and 8th. An additional 0.40 inches was recorded on the

9th. Two subsequent systems moved into Arizona during the period 10-11 January, and 12-19 January. The first resulted in heavier precipitation and runoff in the central part of the state. The latter produced 2 heavy periods of precipitation in the Santa Cruz River basin during the 13th and the 14th of January (1.15 inches recorded at the Tucson NWSO); and during the 19th and 20th of January (0.74 inches recorded at the same station). Most Arizona stations reported 1-3 inches of precipitation from the 16th to through the 19th, as disturbances in the fast, moist flow over the region produced frequent periods of precipitation. Flash flood warnings and watches were issued for many streams as a results of the saturated soil conditions combined with periods of heavy precipitation. A flash flood warning was prompted for the Santa Cruz River from Tucson northward on 19 January. During the latter event the peak discharges on the Santa Cruz River were recorded (or estimated) of 32,400 cfs at Continental (estimated, 2nd greatest flow in history), 37,400 cfs at Tucson (2nd greatest flow in history), and more than 40,000 cfs at Cortaro (estimated by the LAD[3] and others, also the 2nd greatest flow in history). Several large tributaries of the Santa Cruz River in the vicinity of Tucson, Arizona, also recorded significant peak discharges during the initial storm period around 8 January. The peak discharge in Sabino Creek near Tucson (estimated gage height from high-water mark) was 12,900 cfs and the peak-of-record, as was the recorded peak flow in Tanque Verde at Tucson of 24,500 cfs. The recorded peak flow in Rillito Creek at La Cholla Boulevard near Tucson (24,400 cfs) was the 2nd largest peak flow in history.

[3] Source: Santa Cruz River Watershed Management Study, Final Feasibility Report, Appendix E-1, Los Angeles District, U.S. Army Corps of Engineers, August 2001.

6 DISCHARGE-FREQUENCY ANALYSIS - SANTA CRUZ RIVER TRIBUTARIES

6.1 GENERAL. The following table contains hydrologic information, including peak discharges for tributaries of the Santa Cruz River in the Study Area. The locations of these tributaries are shown in maps accompanying reports "a" and "b" as referenced in Section 2 of this report.

Table 2: Pima County Discharge-Frequency Relationships

		Frequency, years						
Stream Name	DA, sq. mi.	500	100	50	25	10	5	2
			Peak Discharges: Santa Cruz Tributaries, cfs					
Hughes Wash	8.34		2376	1875	1258	738	334	93
Santa Clara Wash	0.39		389	314	221	143	86	47
El Vado Wash	2.29		1558	1327	1003	716	474	287
Valencia Wash	1.64		1510	1292	1026	721	441	230
Airport Wash	22.73		5164	3981	2691	1549	740	346
Wyoming Wash	0.70		877	719	519	335	184	82
Irvington Wash	0.25		427	343	237	145	75	40
Rodeo Wash	8.39		3453	2839	2448	1340	744	321
Julian Wash	43.53		5962	6697	3202	1901	945	389
Mission View Wash	1.62		1802	1538	1201	885	599	355
18th St Wash	3.66		3085	2503	1921	1363	886	523
Cushing St Wash	0.50		1165	993	770	562	375	221
Ajo Wash	1.91		3465	2817	2007	1286	689	242
Enchanted Hills Wash	3.11		3968	3270	2386	1540	801	256
San Juan Wash	1.14		1757	1470	1104	757	423	152
Cholla Wash	1.30		2273	1882	1379	920	529	224
Old W Br Santa Cruz	10.22		6621	5417	3818	2447	1352	397
New W Br Santa Cruz	33.20	14,000	9908	7925	5250	3665	2020	595
Los Reales Road	19.06	10,600	7638	6000	4000	2780	1530	450
			Peak Discharges: Rillito River (Creek) Tributaries, cfs					
Craycroft Wash	3.07		2540	1908		891	568	234
Flecha Caida Wash	1.47		1619	1223		579	372	154
Valley View Wash	4.11		3003	2254		1049	667	275
Finger Rock Wash	6.09		3730	2798		1298	823	339
Camino Real Wash	1.86		1878	1415		667	427	176
Campbell Wash	2.50		2249	1692		793	506	209
Alamo Wash	9.90		4809	3608		1671	1058	438
Alvernon Wash	3.32		2658	1996		931	593	244
Christmas Wash	3.32		2658	1996		931	593	244

Notes: 7900 indicates peak discharge estimated by LAD; 7900 indicates peak discharge provided by PIMA for this current study; 7900 indicates peak discharge provided by PIMA for the El Rio Antiguo study.

PCFCD provided discharge-frequency values for 18 tributaries to the Santa Cruz River within the study reach (bounded on the south by Los Reales Road, and on the north by Congress Street) as indicated in the previous table. The data was contained in a document entitled "Santa Cruz River, Paseo de Las Iglesias, Pima County, Arizona, Feasibility Study, Hydrology Report", dated November 2001. These results were taken from pre-existing hydrologic information generated using rainfall-runoff procedures. In addition to this information peak flow rates for the New West Branch (100-year) of the Santa Cruz River were provided separately. All discharges provided are for locations at the confluence with the Santa Cruz River[4]. At the request of the LAD, Mr. Tom Helfrich of PCFCD provided an expanded list of estimated peak discharges for a range of frequencies (2-, 5-, 10-, 25-, and 50-year) for the New West Branch of the Santa Cruz River at the confluence with the Santa Cruz, as well as an estimate of the 100-year (1% chance annual exceedance probability) peak discharge in the New West Branch of the Santa Cruz River upstream at the Los Reales Improvement District.

No evaluation of these peak flow rates was included in the documentation. Subsequent hydraulic/economic analysis by the LAD required additional information, namely estimates of the 500-year (0.2% annual exceedance probability) peak flow rate in the New West Branch of the Santa Cruz River at the confluence with the Santa Cruz, and at the Los Reales Improvement District. At the latter location, the only available peak flow rate was for the 100-year event. Hence, two additional tasks remained:

(1) Evaluate the discharge-frequency values provided.

(2) Estimate the peak flow rates for the 500-year event for the New West Branch at the Los Reales Improvement District (drainage area = 19.06 sq. mi.[5]), and at the confluence with the Santa Cruz River (drainage area = 33.2 sq. mi.[5]). The 500-year discharges were required in order to fully evaluate potential flood damages and possible benefits of flood control alternatives for the New West Branch. In addition to the 500-year discharge, a full range of discharge-frequency values (2-, 5-, 10-, 25-, 50-, and 100-year) was required to perform hydraulic and economic evaluation of without project conditions for the Los Reales Improvement District.

6.2 EVALUATION OF PEAK FLOW RATES FOR SANTA CRUZ RIVER TRIBUTARIES.

Peak discharge-frequency values for the Santa Cruz River tributaries in the study area were evaluated in a generalized manner by plotting the peak flow rates against drainage. Linear

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[4] Except for the New West Branch of the Santa Cruz River at Los Reales Road (the Los Reales Improvement District), which is upstream of the confluence with the Santa Cruz River.

[5] Drainage Area (DA) provided by Pima County.

regression relationships for the log-discharge against the log-DA were developed for each frequency (2-, 5-, 10-, 25-, 50-, and 100-year[6]).

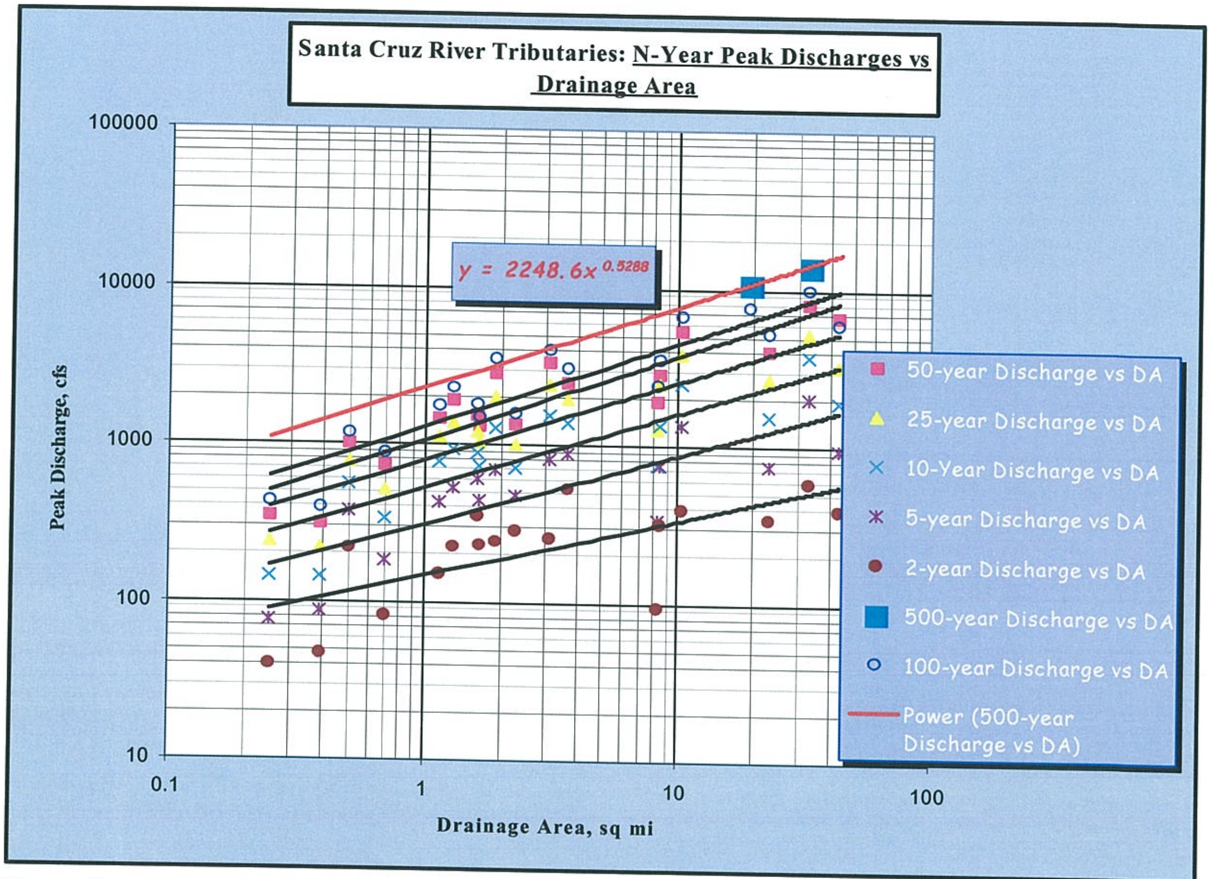

Figure 2. N-year Peak Discharge vs Drainage Area Curves - Santa Cruz River Tributaries.

A reasonable and consistent family of regression curves resulted from this analysis (refer to Figure 1, above). For comparison purposes, peak flow rates for tributaries of the Rillito River (Creek), recently determined by PCFCD[7], were included in the plots and compared to the regressed curves (refer to the following Figures 2-7.

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[6] Referred to hereinafter as "n-year" discharges or curves.

[7] El Rio Antiguo, Rillito River Environmental Restoration, Documentation for Hydrologic Studies, prepared by Pima County Department of Transportation and Flood Control District, Flood Control Engineering Division, for the U.S. Army Corps of Engineers, Los Angeles District, March 2002. Based upon regional equations for Southern Arizona (Region 13, Figure 42 and Table 17) from the USGS report "Methods for Estimating Magnitude and Frequency of Floods in Southwestern United States", 1994.

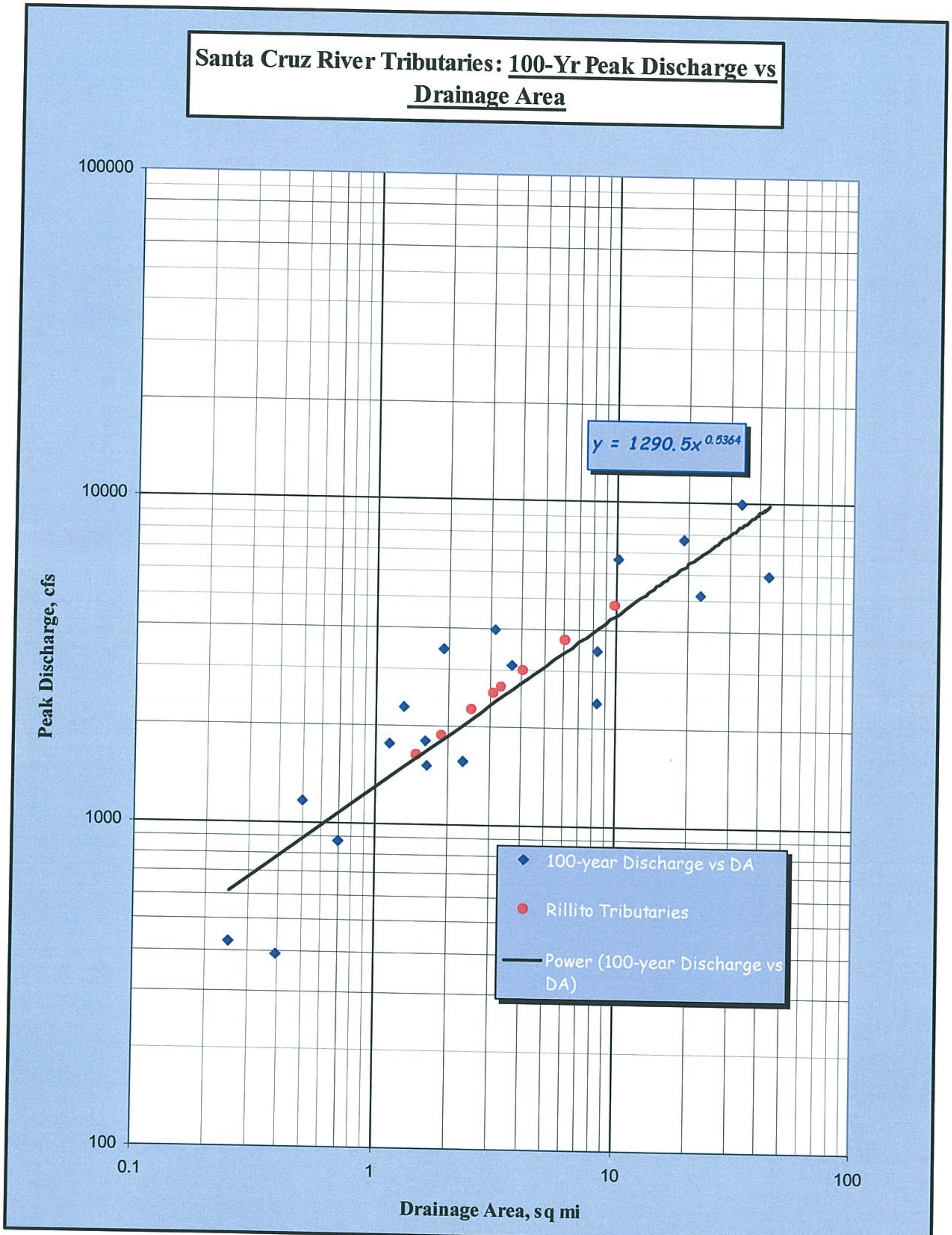

Figure 3. 100-yr Peak Discharge vs Drainage Area - Santa Cruz River Tributaries.

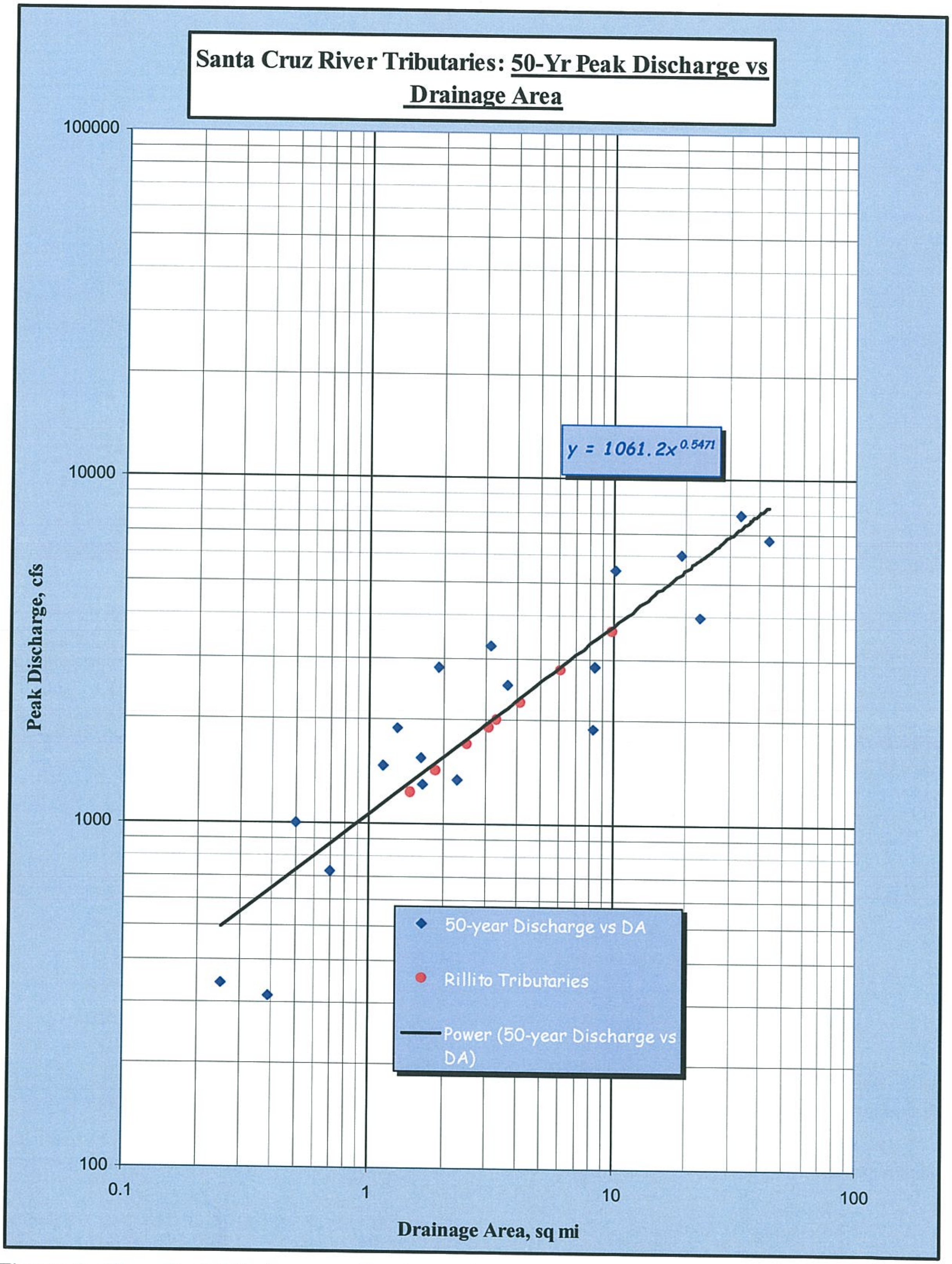

Figure 4. 50-yr Peak Discharge vs Drainage Area- Santa Cruz River Tributaries.

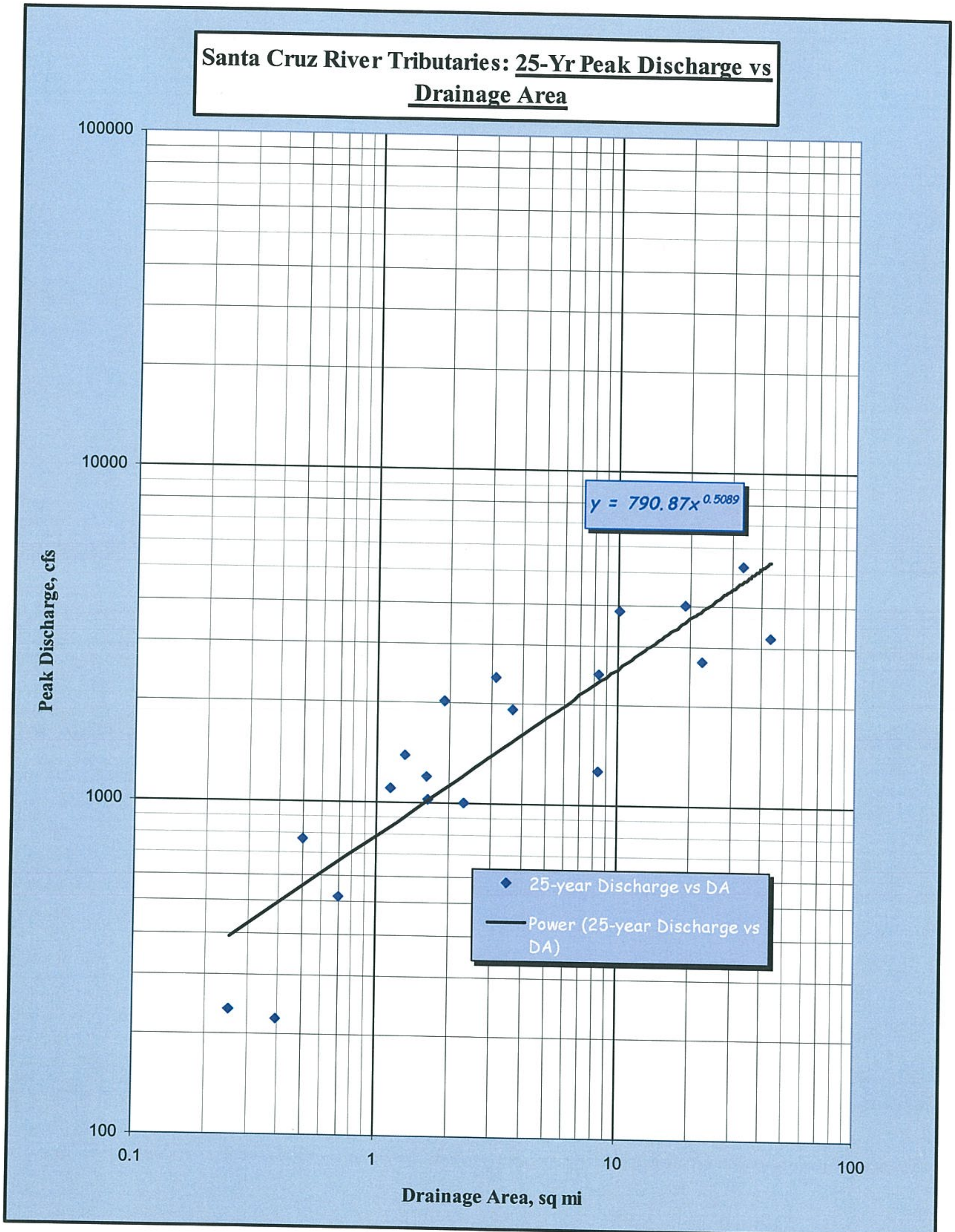

Figure 5. 25-yr Peak Discharge vs Drainage Area - Santa Cruz River Tributaries.

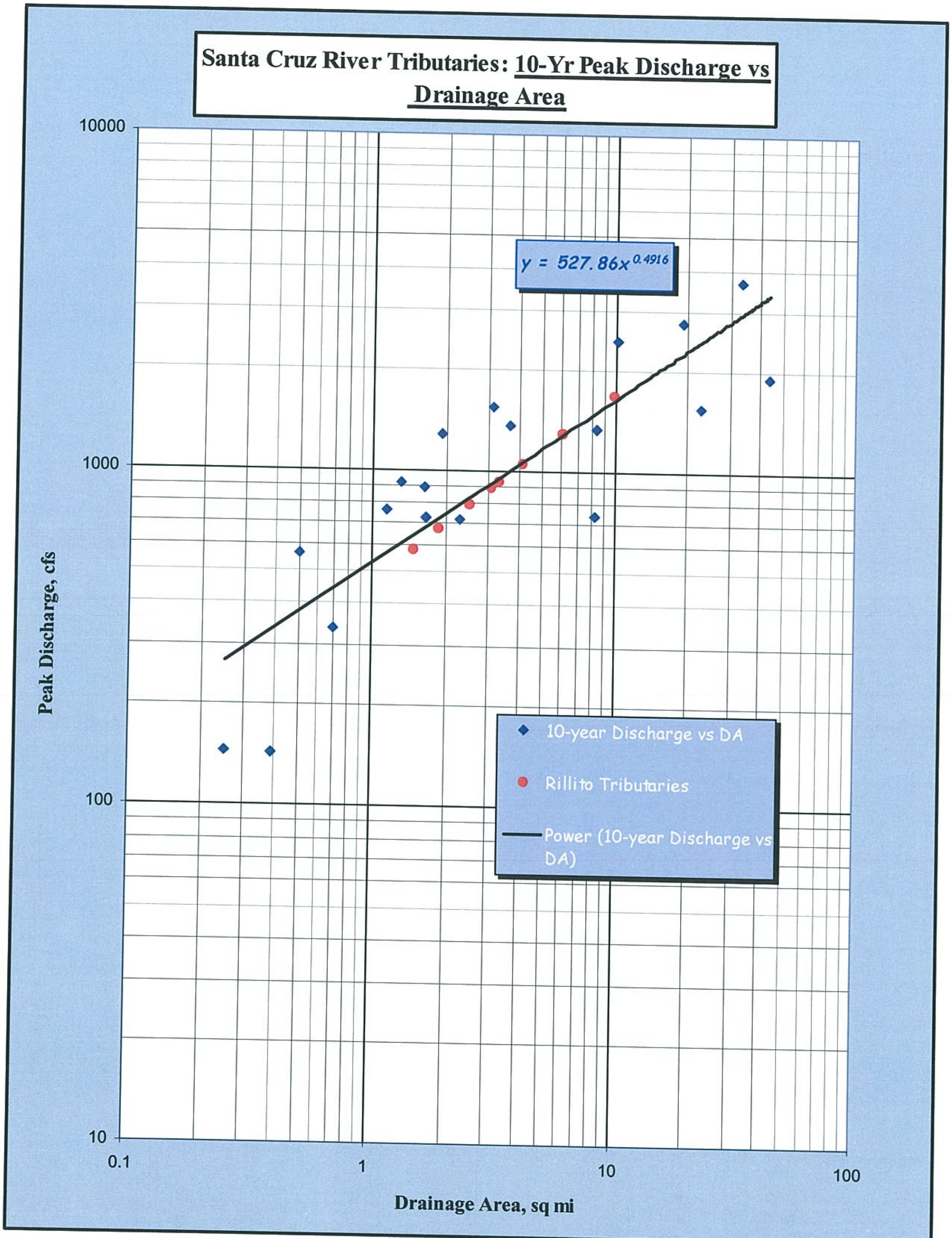

Figure 6. 10-yr Peak Discharge vs Drainage Area - Santa Cruz River Tributaries.

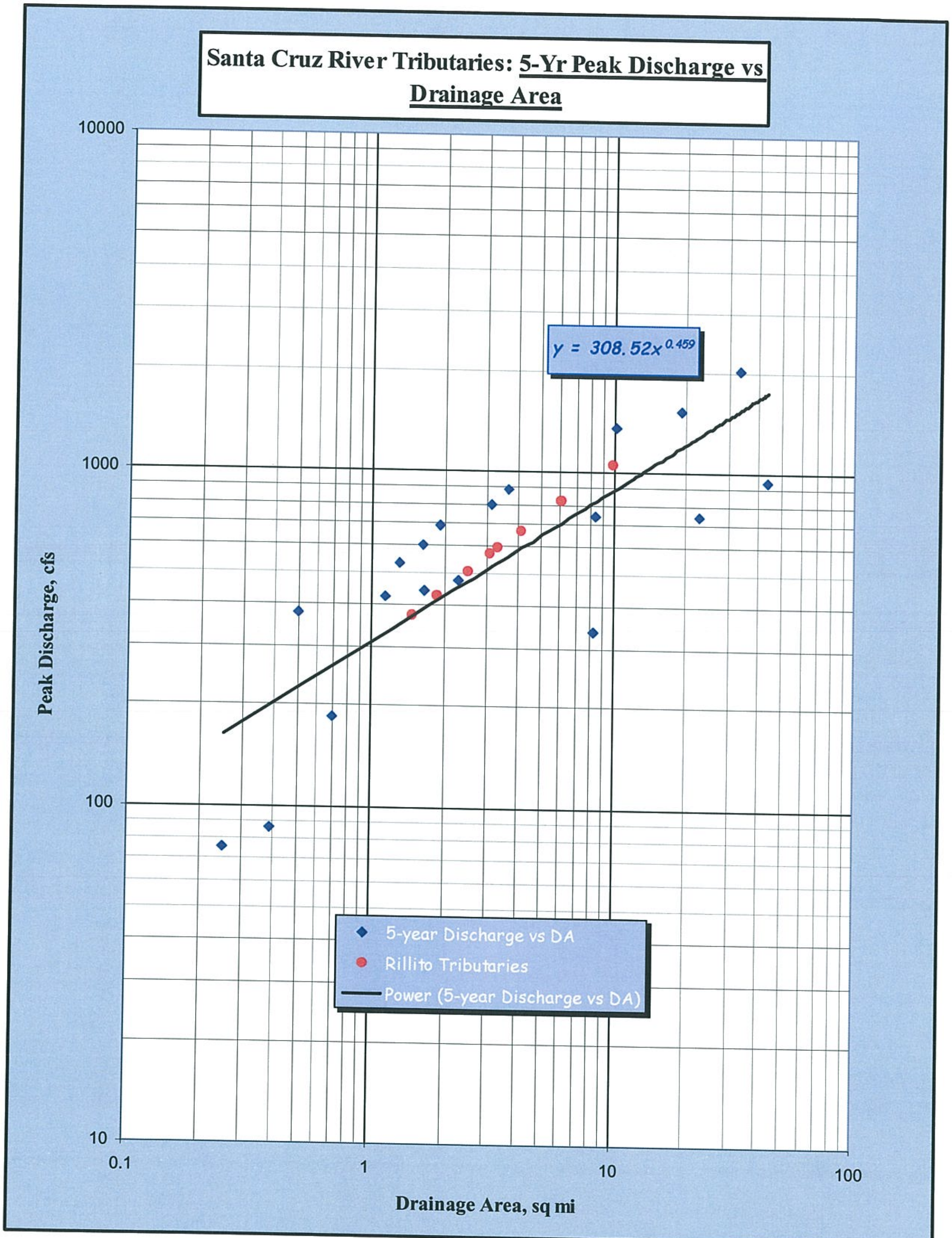

Figure 7. 5-yr Peak Discharge vs Drainage Area - Santa Cruz River Tributaries.

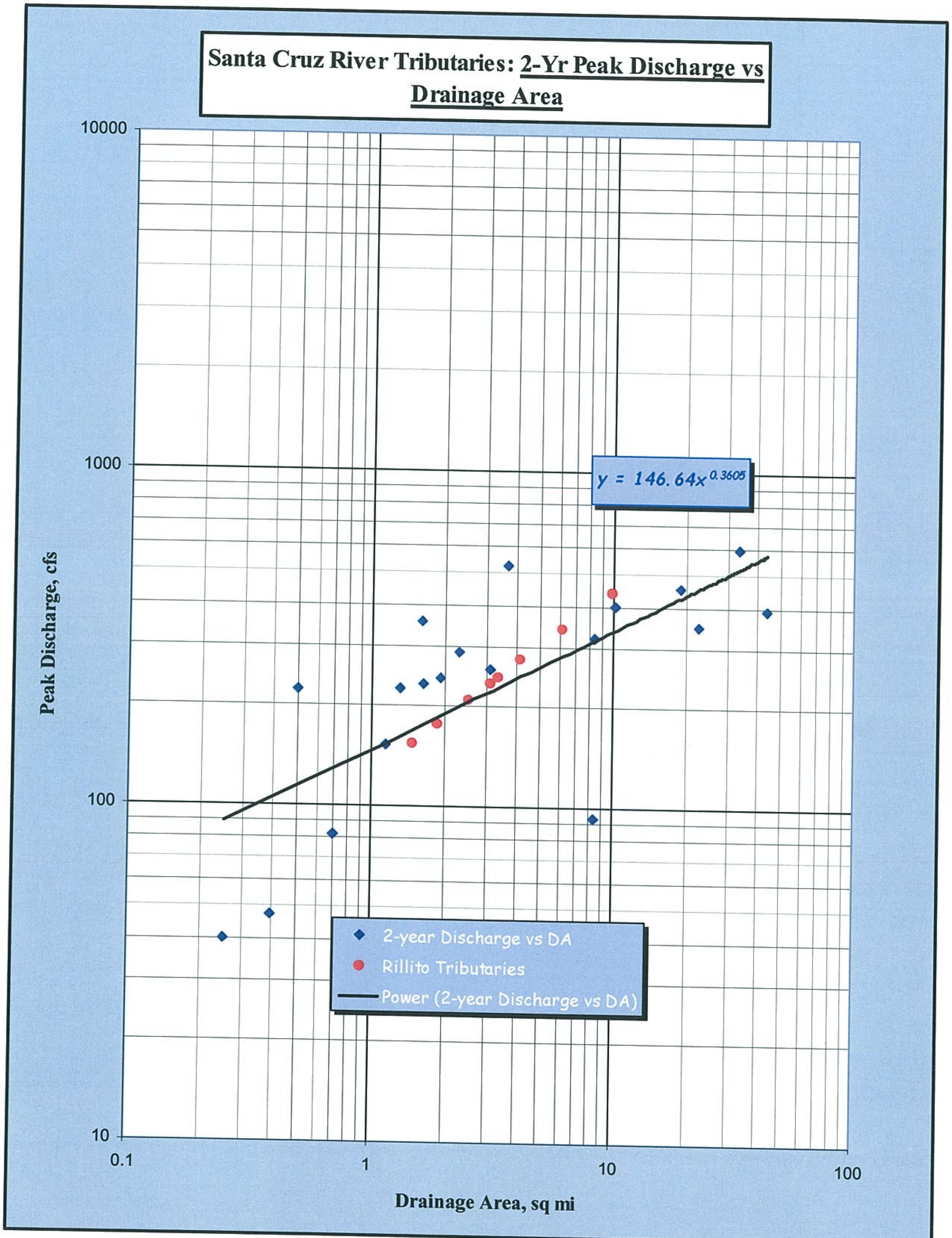

Figure 8. 2-yr Peak Discharge vs Drainage Area - Santa Cruz River Tributaries.

In all instances the Rillito tributary inflow compared well to the regression curves for the Santa Cruz River tributaries. Since the Rillito peak flow rates were developed directly from the USGS regional equations, and since these flow rates are consistent with the regression curves developed from the Santa Cruz River tributary flow rates, it is apparent that the Santa Cruz River tributary flow rates are likewise consistent with the USGS regional equations. Hence, the peak flow rates generated for the Santa Cruz River are likewise consistent with peak flows rates recently developed for the nearby Rillito River (Creek), and are suitable for use in this study.

6.3 ESTIMATION OF PEAK FLOW RATES FOR NEW WEST BRANCH TRIBUTARY OF THE SANTA CRUZ RIVER.

6.3.1 *N-year Discharges at Los Reales Improvement District.* Consideration was given to directly utilizing the n-year regression curves for estimation of peak flow rates in the New West Branch of the Santa Cruz River at the Los Reales Improvement District. However, since the peak flow rates for the downstream location (at the confluence with the Santa Cruz River) were > the regressed value for that drainage area size, it is likely that use of the regression curves to estimate upstream peak flow rates would yield discharges which were inconsistent with the downstream flows. Hence, the peak flow rates at the Los Reales Improvement District were estimated by prorating the downstream peak discharges by ratio of the square root of the respective drainage areas[8] for each n-year return period. Variation of peak flow rate in direct proportion to the square root of drainage area is not uncommon in hydrologic applications. The use of this ratio (0.758) was supported by two independent computations:

(1) The peak 100-year flow rate computed for the Los Reales Improvement District, 7638 cfs[9], is approximately 77% of the peak flow rate for the New West Branch at the mouth, 9908 cfs.

(2) The n-year regression curves indicate that the peak flow rates for a DA of 19.06 sq. mi. are proportionally about 75% of the flow rates for a DA of 33.20 sq. mi. for the entire range of frequencies.

6.3.2 *Discharge-Frequency Curve for New West Branch at the Confluence with the Santa Cruz River.* In order to provide an estimate of the 500-year peak discharge in the New West Branch consistent with the discharges provided by PCFCD, several approaches could have been taken. The USGS regional equations (paragraph 2.5) do

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[8] The computed ratio is $(19.06^{1/2}/33.20^{1/2}) = 0.758$. The 100-year discharge reported, 7638 cfs, was provided by PCFCD (refer to the following footnote).

[9] Re: "Request for a Letter of Map Revision for the Los Reales Improvement District Located in Pima County Arizona, and in the City of Tucson, Arizona" prepared by Arroyo Engineering, Inc. and submitted to the Pima County Department of Transportation and Flood Control District and the City of Tucson Department of Transportation in December 1994.

not include peak flow rates beyond the 100-year event. Rainfall-runoff modeling, consistent with that used to develop n-year peak discharges could have been used. However, in order to provide information for Risk/Uncertainty Analysis (including both rare and frequent events) and to maintain consistency with the set of n-year discharges, the approach taken was to develop a synthetic discharge-frequency relationship. A quasi-analytical[10] discharge-frequency curve was fitted to the computed values provided by PCFCD. This curve was generated using a trial-and-error procedure based upon developing a set of log-Pearson Type III parameters that would yield equivalent discharges.

6.3.2.1 **Estimated Log-Pearson Type III Distribution Synthetic Parameters.** The following parameters describe a continuous curve consistent with the n-year discharge-frequency values provided by PCFCD:

1) Log-Mean = 2.681
2) Standard Deviation = 0.750, and
3) Skew = -0.80.

6.3.2.2 **500-Year Discharges for New West Branch Tributary.** The 500-year discharge for the New West Branch of the Santa Cruz River at the mouth (the confluence with the Santa Cruz River) was estimated from the quasi-analytical discharge-frequency curve constructed using these synthetic parameters. The intersection of the 0.2% annual exceedance probability event (the 500-year event) and the peak discharge is approximately 14,000 cfs. Subsequently the 500-year peak flow rate for the New West Branch at the Los Reales Improvement District was estimated in the same manner as were the other frequency events by applying the square root of the drainage area ratio to the downstream 500-year peak discharge (0.758 x 14,000 cfs = 10,600 cfs).

6.3.3 *Discharge-Frequency Curve for New West Branch at the Los Reales Improvement District.* Again, in order to provide information for Risk/Uncertainty Analysis (including both rare and frequent events), a synthetic discharge-frequency relationship was developed from the n-year discharges. A quasi-analytical discharge-frequency curve was fitted to the computed values prorated from the downstream discharges, and the 100-year discharge provided by PCFCD. This curve was generated in the same manner as the curve for the New West Branch at the

[10] The procedure is referred to as "quasi-analytical" because the basis for the curve-fitting parameters was a set of synthetic statistics which yielded a discharge-frequency curve consistent with the discrete values provided by PCFCD. The statistics were based upon the likelihood that the n-year values provided were consistent with a log-Pearson Type III Distribution.

confluence, using a trial-and-error procedure based upon developing a set of log-Pearson Type III parameters that would yield equivalent discharges.

6.3.3.1 **Estimated Log-Pearson Type III Distribution Synthetic Parameters.** The following parameters describe a continuous curve consistent with the n-year discharge-frequency values:

1) Log-Mean = 2.555
2) Standard Deviation = 0.755, and
3) Skew = -0.80.

6.3.4 *Summary and Comparison of Results.* The following table presents a summary of the discharge-frequency values provided by PCFCD for the New West Branch tributary, along with the supplemental discharge-frequency estimates made by the LAD. Included are a comparison of these values to synthetic or quasi-analytical results and statistical parameters generated within this study to augment the data and to facilitate Risk/Uncertainty Analysis.

Table 3: Discharge-Frequency Relationships - New West Branch of Santa Cruz River

Name	DA, sq. mi.	Frequency, years: 1000	500	200	100	50	25	10	5	2
LOCATION		**Peak Discharges: Santa Cruz Tributaries - New West Branch, cfs**								
at Santa Cruz River	33.2	16000	14000	12000	9908	7925	5250	3665	2020	595
at Los Reales Road	19.06		10600	8900	7638	6000	4000	2780	1530	450
		Exceedance Probability, %								
		0.1	0.2		1	2	4	10	20	50

Discharges from Computed Statistics		Exceedance Probability, %: 0.1	1	5	10	30	50	70	90
LOCATION		**Peak Discharges: Santa Cruz Tributaries - New West Branch, cfs**							
at Santa Cruz River	33.2	16000	9680	5200	3550	1350	600	230	47
at Los Reales Road	19.06	12200	7390	3950	2700	1020	450	185	35

Computed Statistics	M	S	G
at Santa Cruz River confluence	2.681	0.75	-0.8
at Los Reales Road	2.555	0.755	-0.8

Data provided by Pima County

Data computed by LAD-COE

7 SYNTHETIC FLOOD HYDROGRAPHS - Santa Cruz River at Tucson

7.1 VOLUME-FREQUENCY RELATIONSHIPS. In order to develop synthetic flood hydrographs (*Balanced Hydrographs)* for use in sedimentation analysis for the Santa Cruz River within the study area, a necessary first step is to develop volume-frequency relationships.. **Note: volume-frequency is a term for discharge-frequency relationships incorporating a series of duration-discharges, e.g. peak or instantaneous flow, 1-day flow, 2-day flow, 3-day flow, etc. The resulting discharge-frequency relationships are typically displayed as a family of curves.** Durations are selected to provide adequate definition for the stream/drainage area of interest. Data is typically derived from annual maxima for each duration of interest, and represents the maximum average flow (or volume) from a contiguous set of observed discharges. The best source of contiguous duration data is a recording streamgage. For the Santa Cruz River in the study area, recorded or systematic daily flow record is available from the USGS (Station 09482500) from as early as 1905 (although the early record is fragmented) to the present at a series of closely situated gaging sites at/near Congress Street in Tucson, Arizona.

For this current sediment transport analysis volume-frequency relationships developed for the July 1990 Corps of Engineers Report (ref. 2.8), SANTA CRUZ RIVER, Hydrologic Documentation for Feasibility Studies, Lower Santa Cruz River Flood Control Study, Pinal County, Arizona, were selected for incorporation into this study (Plate 24 of that study). Likewise, peak discharges were available from the report (ref: 2.3) SANTA CRUZ RIVER WATERSHED MANAGEMENT STUDY, APPENDIX E-1, Los Angeles District, U.S. Army Corps of Engineers, August 2001. The peak discharge-frequency values[11] were developed from a "mixed population" analysis, while the volume-frequency values were developed from an analysis of annual maxima. **Note: it was considered reasonable that the largest duration flows for each year (annual maxima) would be adequate to address sedimentation issues, since the approach taken was to establish a sediment budget rather than perform a detailed sediment routing procedure.** Inspection of the volume-frequency values indicated that durations of 3-days adequately described flood events. For example, the 100-year, 3-day volume is 48,790 ac-ft. Contrasted to that, the 100-year, 5-day volume (not shown in table below) is 50,580 ac-ft, an increase of only 1790 ac-ft (< 4%) over the additional 2-day period, or an additional average flow of only 450 ft^3/s. The "blended" data is shown in the following table.

[11] The peak discharge-frequency values were also used for the flood control analysis of the Santa Cruz River, and are included in the following table.

Table 4: Santa Cruz River at Tucson: Volume-Frequency Values

Frequency (years)	Flow Duration			
	Instantaneous	1-Day	2-Day	3-Day
	Average Discharge for each Duration			
500	120000	33000	22000	16000
200	75000	22000	15000	11000
100	55000	17000	11000	8200
50	35000	12000	8000	5800
20	20000	7600	5275	3600
10	14000	5000	3300	2350
5	9500	3050	2000	1450
2	4900	1300	880	430

Note: all duration discharges shown are in ft³/s.

7.2 BALANCED HYDROGRAPH DEVELOPMENT. A *Balanced Hydrograph* is a hypothetical flood event having the same probability of exceedance for every duration. As such, it is a convenient tool to analyze situations requiring both volumetric information, where storage may exert an influence (such as impoundments or channel routing and overflow mapping), as well as peak information, which is necessary for channel capacity determination and outlet sizing. *Balanced Hydrographs* are typically developed from volume-frequency relationships, in order to establish boundary conditions (i.e. duration discharges for each frequency of interest) for computation/interpolation of flow rate versus time. In this case the boundary conditions were limited to the peak discharge, and the 1-, 2-, and 3-day average discharges for each n-year frequency (please refer to the preceding table). For example, the boundary conditions to describe the 100-year *Balanced Hydrograph* (or 1% chance annual exceedance flood) were the 1% annual exceedance probability instantaneous discharge (55,000 ft^3/s), the 1% annual exceedance probability 1-day average discharge (17,000 ft^3/s), the 1% annual exceedance probability 2-day average discharge (11,000 ft^3/s), and the 1% annual exceedance probability 3-day average discharge (8200 ft^3/s). Since each duration discharge is selected from a consistent family of frequency curves, and these duration discharges are used as boundary conditions, it is reasonable to assume that the flow rate for any intermediate duration (e.g., $Q_{nstantaneous} < Q_{ntermediate\ duration} < Q_{1\text{-}day}$, and $Q_{1\text{-}day} < Q_{ntermediate\ duration} < Q_{3\text{-}day}$) within these hypothetical flood hydrographs has the same frequency of exceedance.

Balanced Hydrographs can be developed in a variety of ways, including manual or graphical interpretation of the volume-frequency results. Such synthetic floods can also be developed in an automated procedure using the HEC-1 Flood Hydrograph Package (The "HB-card" allows the user to input boundary conditions for automatic processing; when linked to a set of initial conditions, i.e. a "pattern" input hydrograph – in this case the October 1983 flood was utilized - there is sufficient hydrologic information to compute hydrograph ordinates for each event). Required input includes the computation interval and duration of flow, along with a pattern hydrograph and boundary conditions. Use of the HEC-1 package allows easy graphical depiction of the resulting *Balanced Hydrographs* through use of the HEC-DSS (data storage system). *Balanced Hydrographs* for each of the n-year synthetic flood events described are provided in Exhibits 1 through 8; each synthetic flood hydrograph is compared to the "pattern hydrograph" for informational purposes.

8 RISK AND UNCERTAINTY

8.1 GENERAL. "*Risk* involves exposure to a chance of injury or loss. The fact that risk inherently involves chance leads directly to a need to describe and to deal with *uncertainty.* Because of the lack of technical knowledge of the complex interaction of uncertainties in predicting hydrologic, hydraulic, and economic functions and because of the complexities of the mathematics required to do otherwise, the engineer must describe the uncertainty in choice of the hydrologic, hydraulic, and economic functions, describe the uncertainty in the parameters of the functions, and describe explicitly the uncertainty in results when the functions are used. Through this risk and uncertainty analysis (also known as uncertainty propagation), and with careful communication of the results, more informed decisions can be made." Reference 2.4.

ER-1105-2-101 requires "risk-based analysis" for Feasibility studies for several aspects of these studies, including Hydrology. The analysis of the Santa Cruz River in the study area as well as the New West Branch tributary includes hydrologic uncertainty in the determination of average annual damages. Since the hydrologic analysis of both the mainstem Santa Cruz River and the New West Branch tributary were non-traditional (i.e. the final results were not portrayed by a set of analytical parameters[12]), the accompanying uncertainty estimates were developed in accord with ETL-1110-2-537 (October 1995), UNCERTAINTY ESTIMATES FOR NON-ANALYTICAL FREQUENCY CURVES.

8.2 PREVIOUS EXPERIENCE . Economic analysis based upon Risk and Uncertainty has brought to light some conflicts in the sampling process resulting from the use of "graphical" discharge-frequency data. Since the flood data developed in hydrologic analyses typically includes only peak discharges for potentially- "damaging" events (the mean annual flood event - 2-yr, or 50% annual chance of exceedance - and greater events), the algorithm used to randomly generate a range of possible peak discharges for each event was constrained. Analytically-derived statistics permit random generation of discharges for any frequency event based upon a "normal" distribution (in this case log-Pearson Type III). In order to

[12] Note: the "mixed population" analysis for the Santa Cruz River did involve traditional or analytical procedures for each of the 3 identified storm-producing event types, i.e. *monsoonal, cyclonic, and frontal.* However, no integrated statistics were available for the final, combined product. Hence, the results were treated as "graphical" as far as incorporation into the Flood Damage Assessment model (HEC-FDA). On the other hand, as discussed in Section 6 of this report, quasi-analytical parameters were developed for the New West Branch tributary. Hence these "statistics" were input to the HEC-FDA model for without project damage assessment.

more completely describe the "normal" distribution, it was necessary to estimate frequent flood events (e.g. events more frequent than the mean annual maximum flood). This additional data provided realistic bounds to the sampling process which greatly improved the economic evaluation.

8.3 APPLICATION TO CURRENT STUDY. Risk and uncertainty information was required for the mainstem Santa Cruz River and the New West Branch tributary in order to determine without- project flood damages. The following hydrologic information was generated within this or previous studies and used in conjunction with accompanying hydraulic and economic data to generate risk-based damages for the aforementioned streams.

8.3.1 *Equivalent years of record.*
8.3.2 *Peak discharge-frequency values/curves.*
8.3.3 *Synthetic discharge-frequency curves/parameters*

8.4 EQUIVALENT YEARS OF RECORD. Uncertainty in hydrologic results was accounted for by assigning an *equivalent record length* to both the Santa Cruz River and the New West Branch tributary data, estimated using table 4-5 in EM 1110-2-1619 (Table A-1 of ETL 1110-2-537), with consideration of uncertainty associated with the source, applicability, and length of streamflow record associated with the discharge-frequency values.

8.4.1 *Santa Cruz River*. The discharge-frequency values for the Santa Cruz River (at Tucson, near Congress St.) were considered to be very reliable because of the long-period from which estimated discharges were available, tests made as to consistency of data, and the fact that a complex study for that area had recently been completed which corroborated independent results. As a result, an equivalent record length of 106 years was assigned to the Santa Cruz River data (extended to 1891 because of historic information; refer to ref. 2.3 for further information/discussion).

8.4.2 *New West Branch Tributaries*. The regional analysis used to evaluate/generate the Table 3 discharges was based upon an average of 21 years of systematic record (please refer to Figure 42, ref. 2.6) . Hence, the equivalent years of record assigned to the 2 New West Branch tributary locations is 21.

8.5 PEAK DISCHARGE-FREQUENCY VALUES/CURVES.

8.5.1 *Santa Cruz River*. Discharge-frequency values for the Santa Cruz River at Tucson (Drainage Area = 2222 sq.mi.) are listed in Table 4. For risk and uncertainty analysis the list of discharges was expanded to provide a more complete, quantitative description of the underlying discharge-frequency relationship. Please refer to Table 5, which follows for an expanded summary of the values, and to Figure 8 for the source data (i.e. the discharge-frequency curve) from which these values were obtained.

Table 5. <u>Santa Cruz River at Tucson:</u> Risk/Uncertainty Peak Discharge-Frequency Values

Annual Exceedance Probability	Peak Discharge, ft^3/s
0.002	120000
0.005	75000
0.01	55000
0.02	35000
0.05	20000
0.1	14000
0.2	9500
0.5	4900
0.8	2800
0.9	1450
0.95	1300
0.99	850
0.998	510

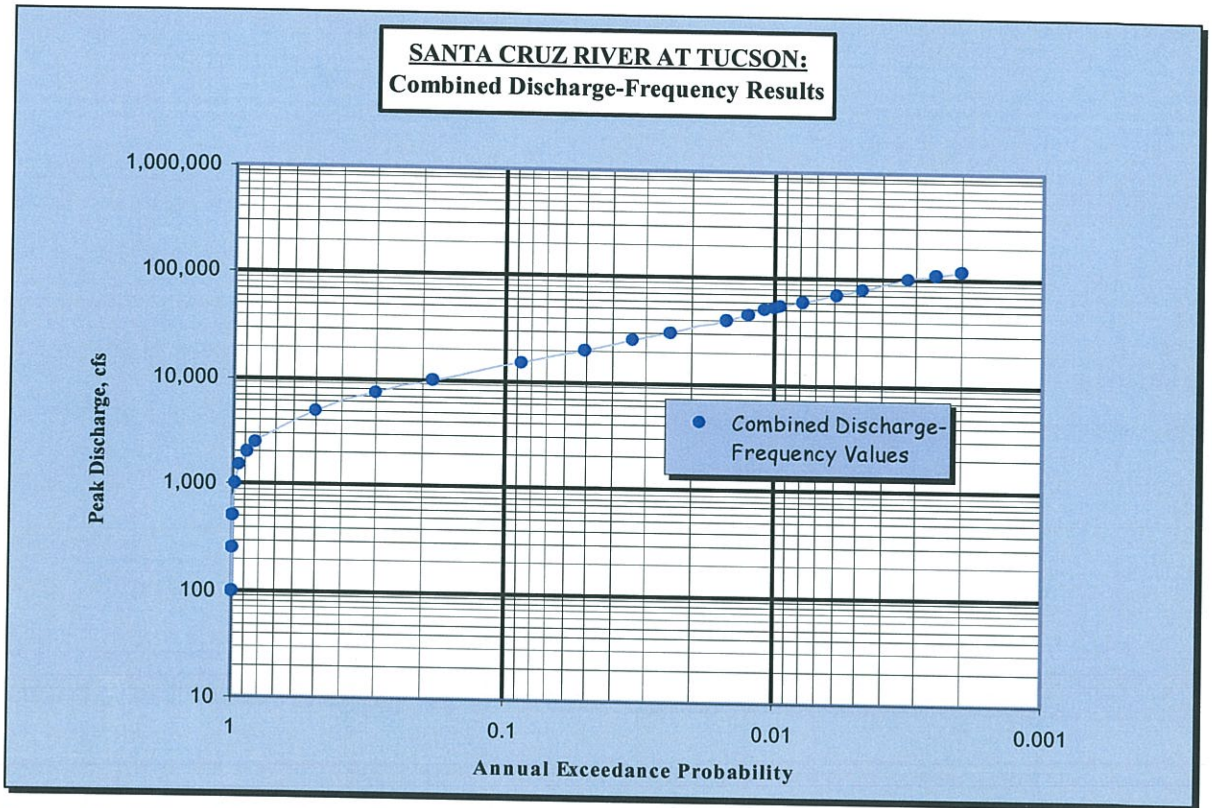

Figure 9. Mixed Population Discharge-Frequency Curve - Santa Cruz River at Tucson.

8.5.2 *New West Branch Tributaries.* Synthetic statistics for the upstream location (at the Los Reales Improvement District) and the downstream location (at the confluence with the Santa Cruz River) were presented in Table 3. Figure 9 (following page) portrays the synthetic discharge-frequency curves generated from these statistics and the discharge-frequency values from which the statistics were developed.

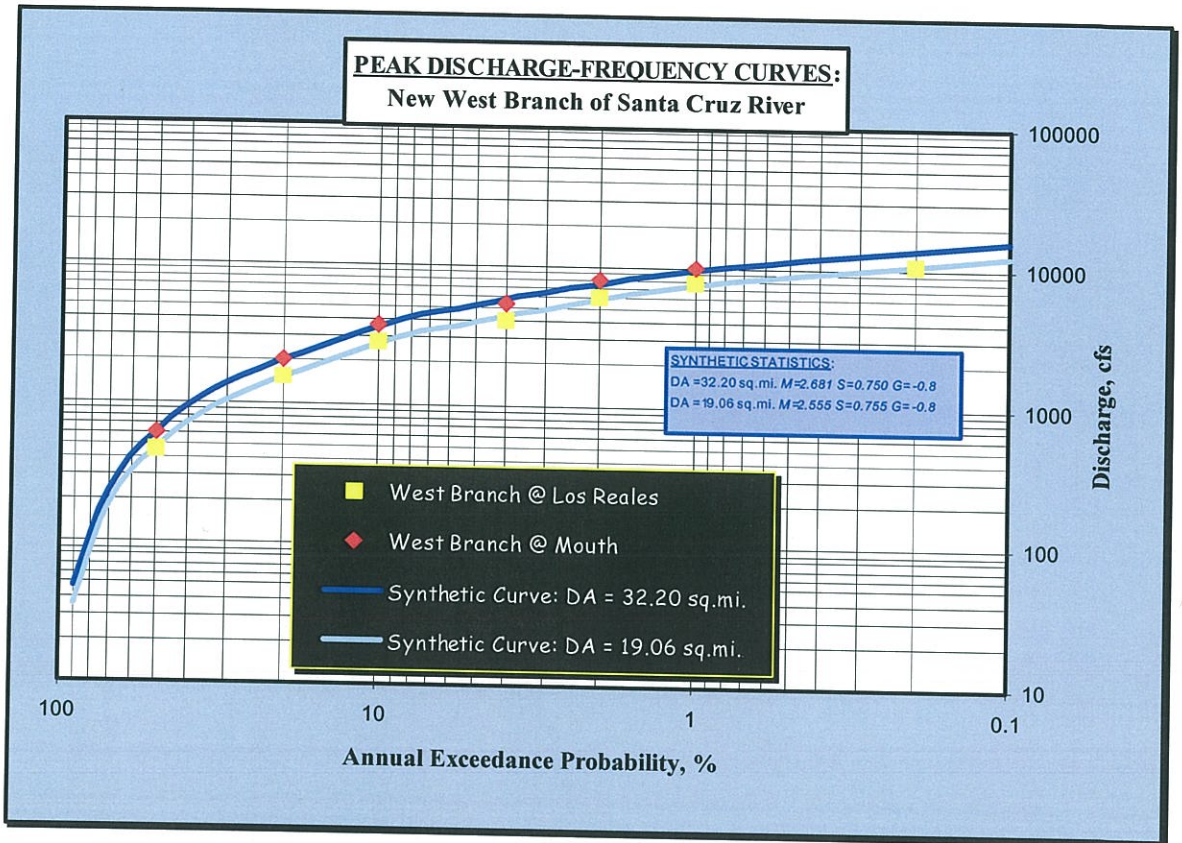

Figure 10. Synthetic Discharge-Frequency Curves - New West Branch Tributary.

EXHIBITS

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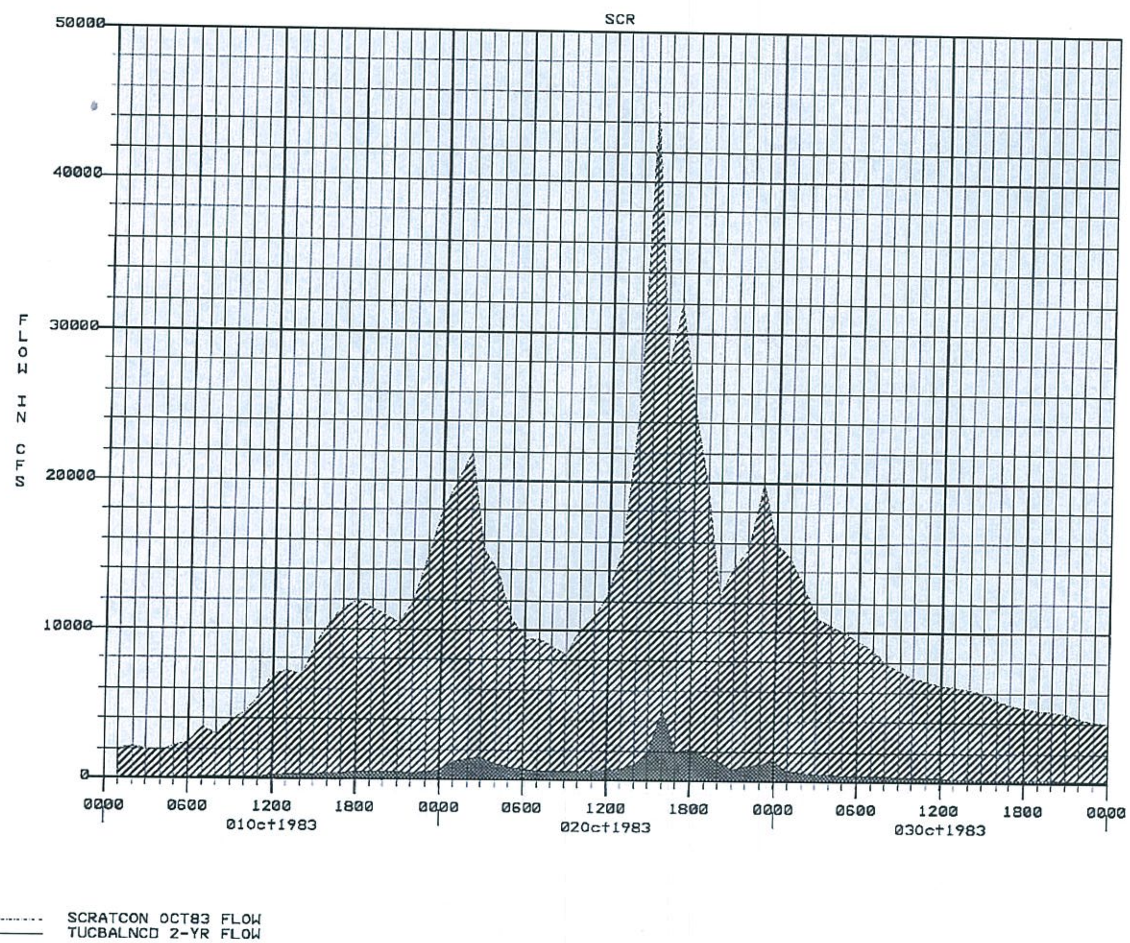

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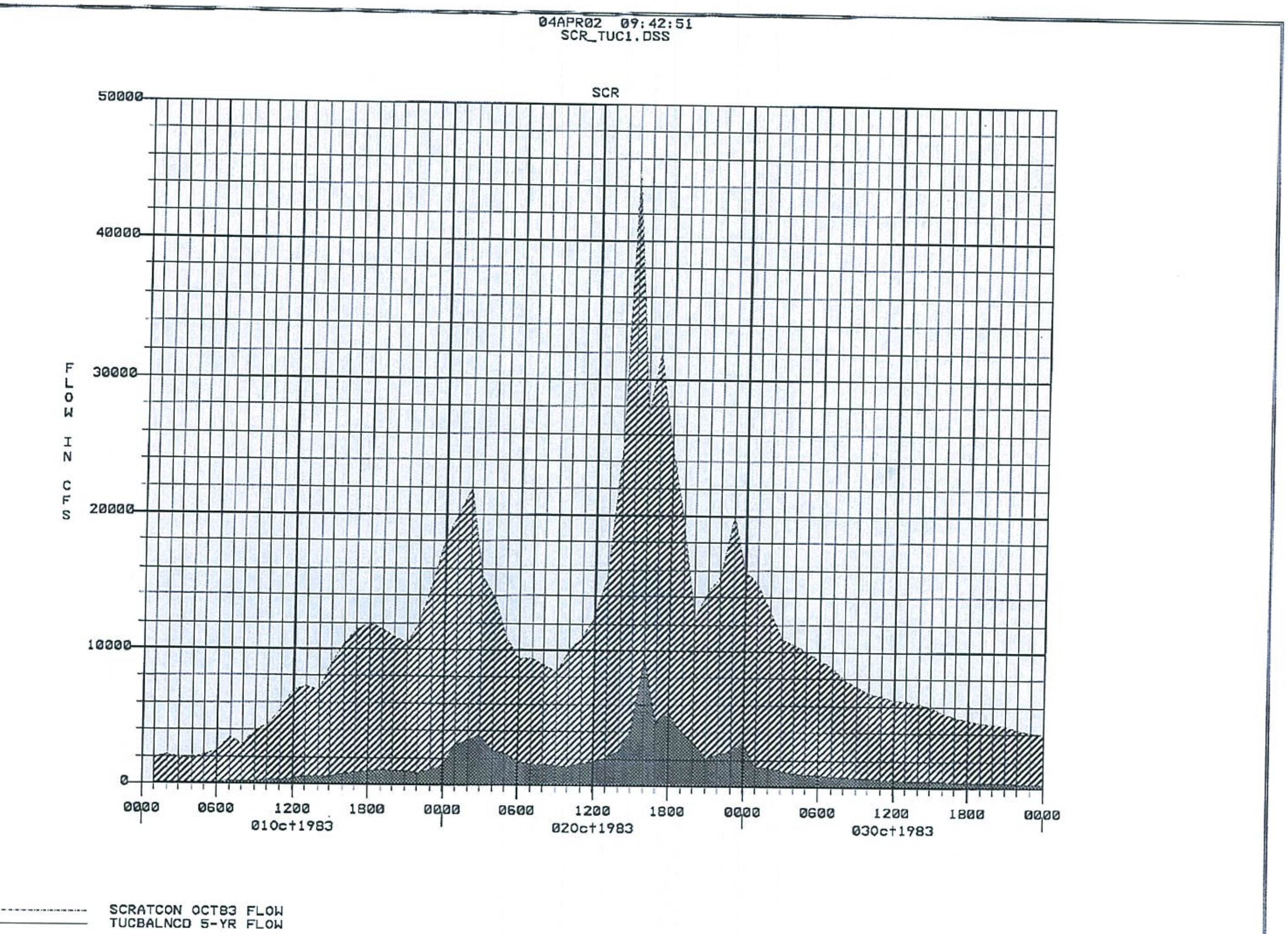

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SCRATCON OCT83 FLOW
TUCBALNCD 5-YR FLOW

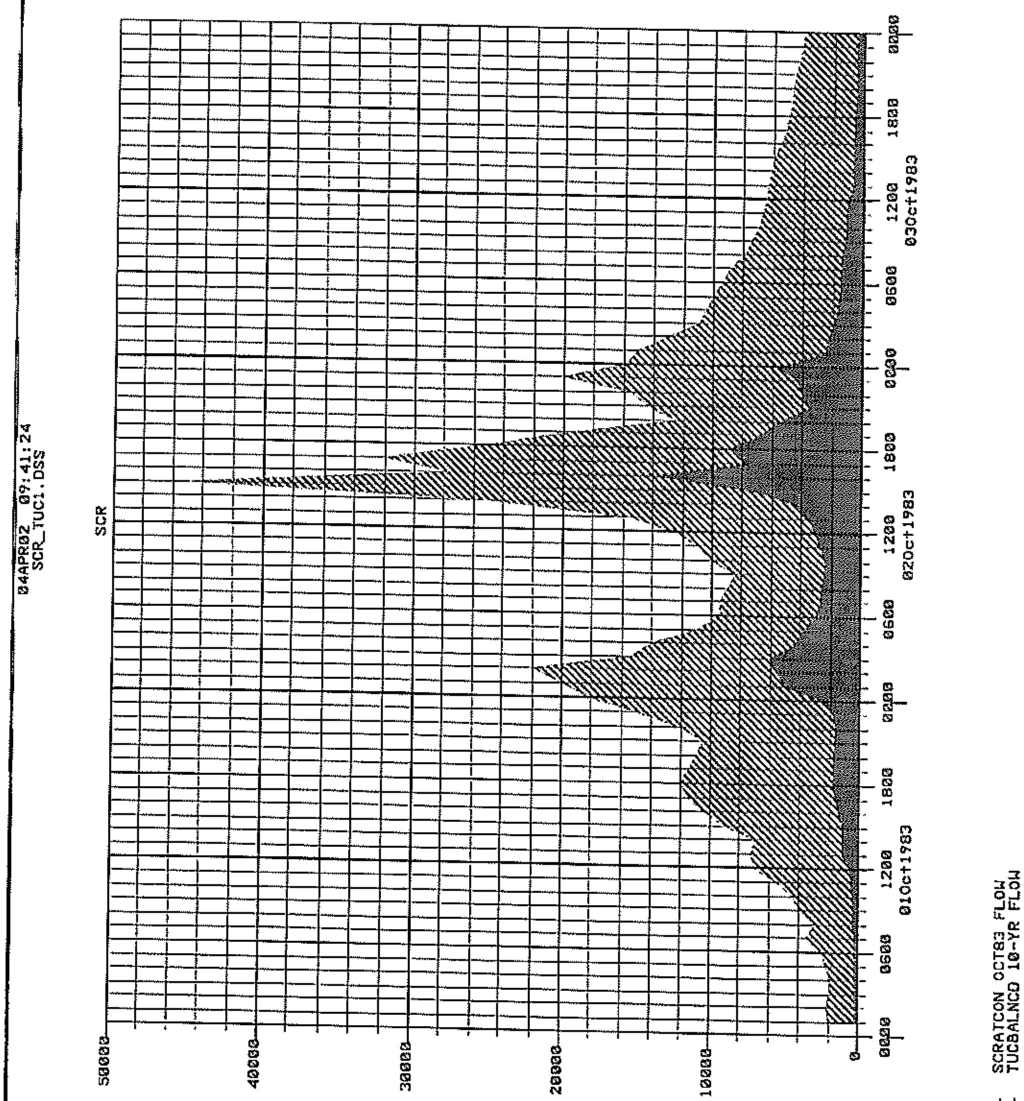

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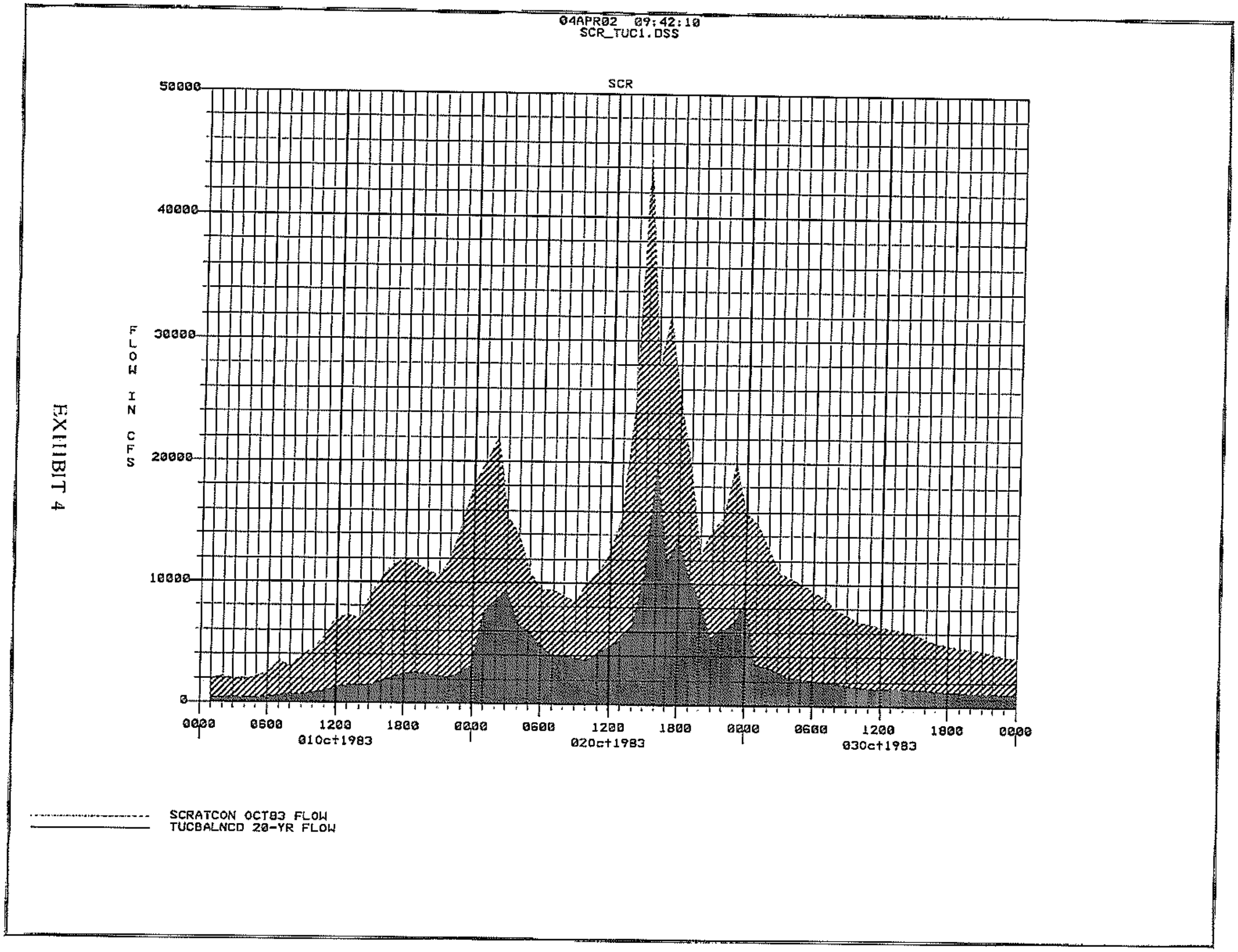
EXHIBIT 3



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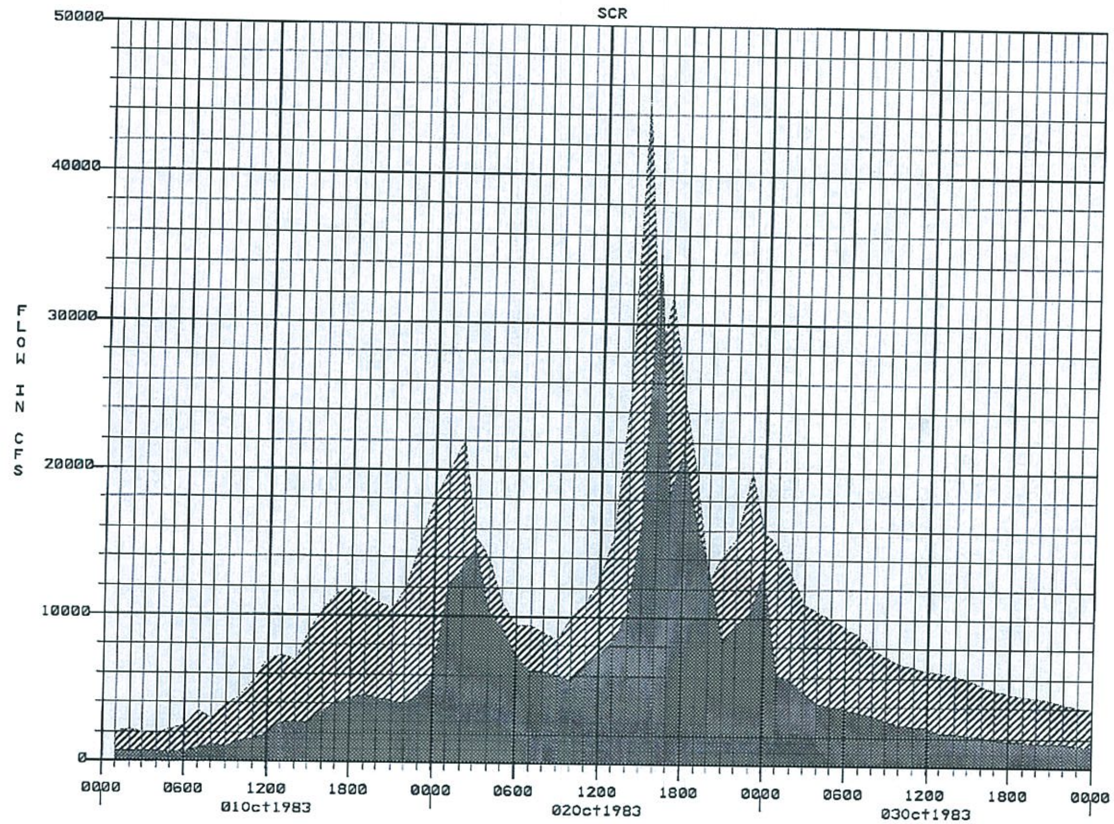
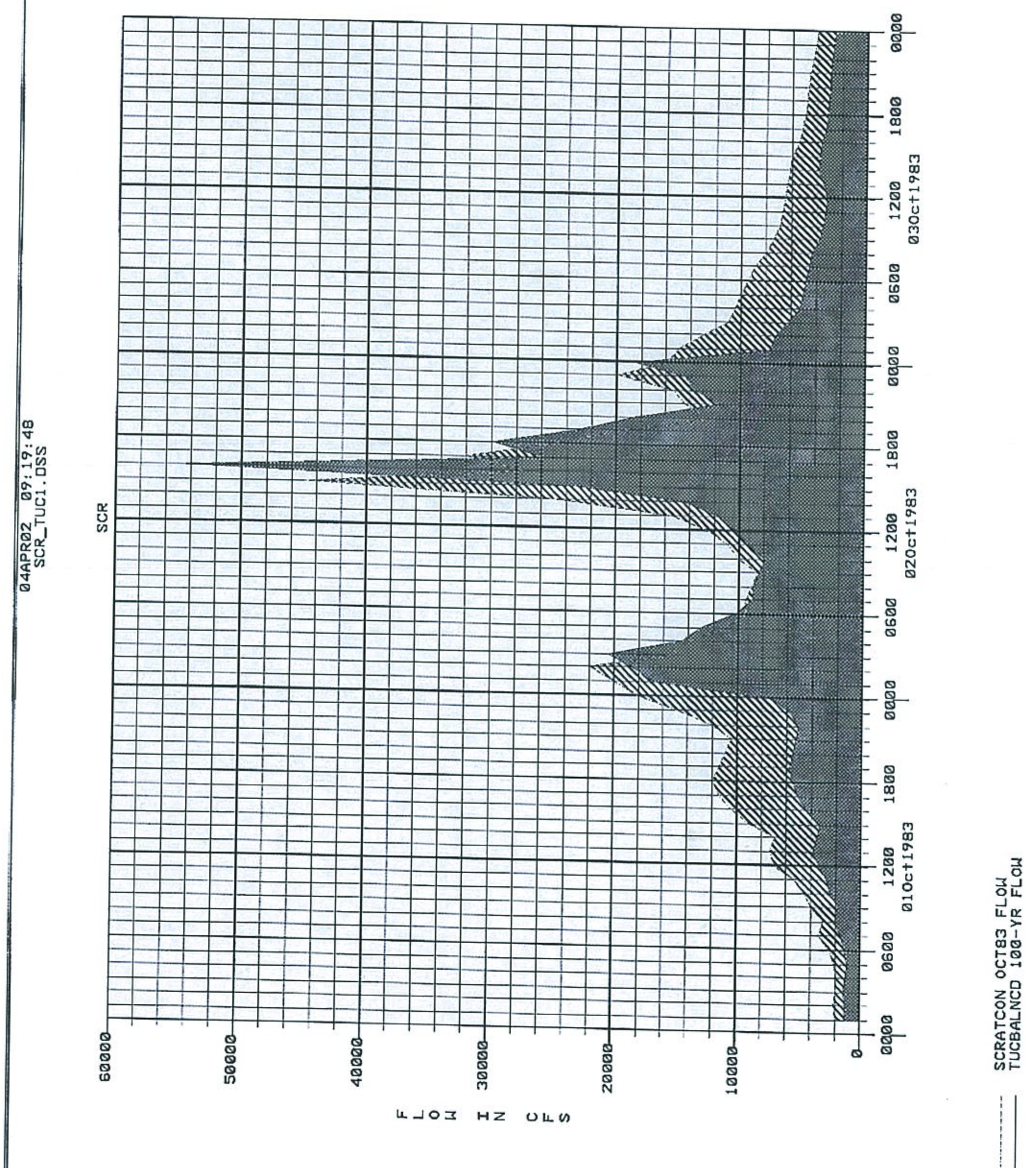


SCRATCON OCT83 FLOW
TUCBALNCD 50-YR FLOW

EXHIBIT 5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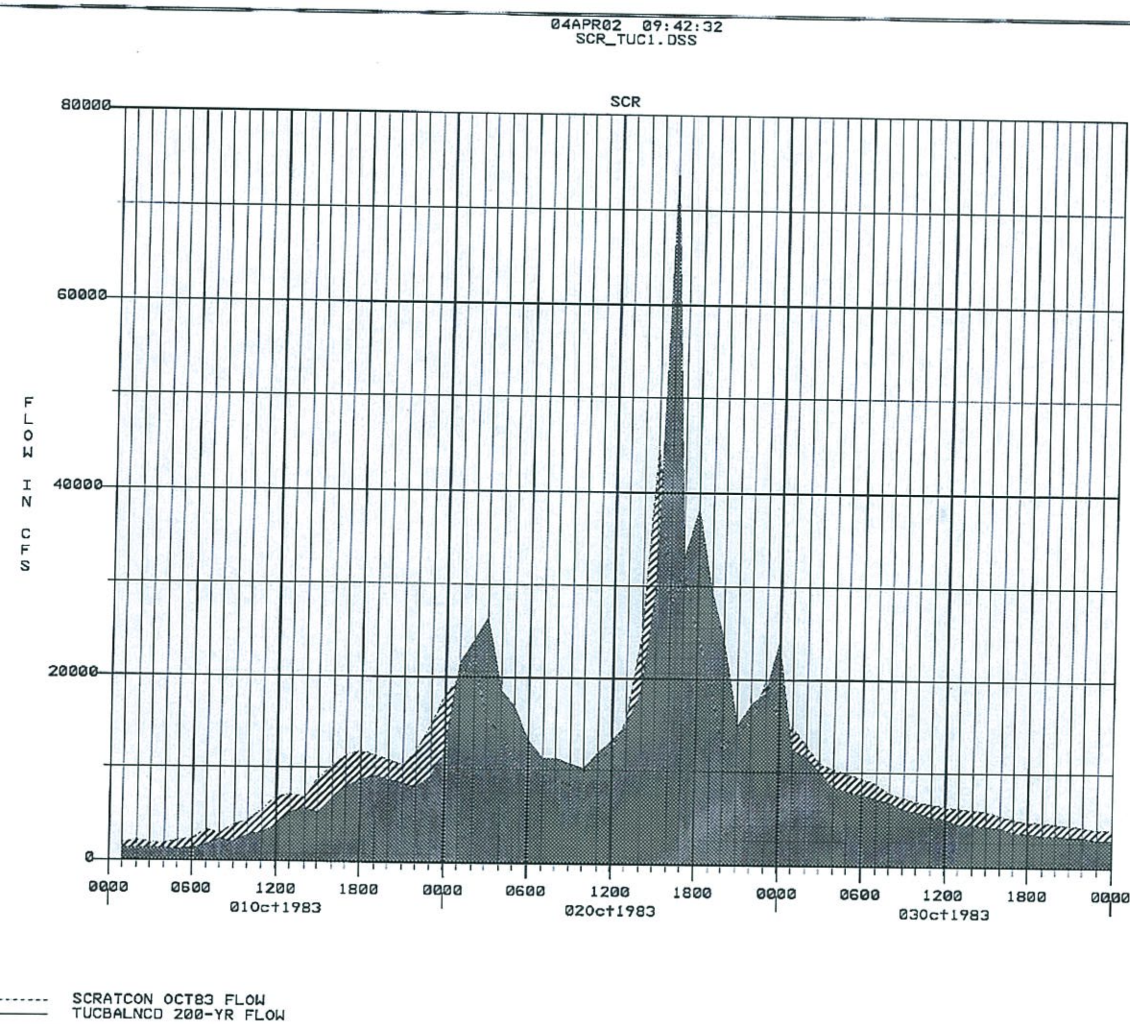
SCRATCON OCT83 FLOW
TUCBALNCD 100-YR FLOW

EXHIBIT 6

EXHIBIT 7



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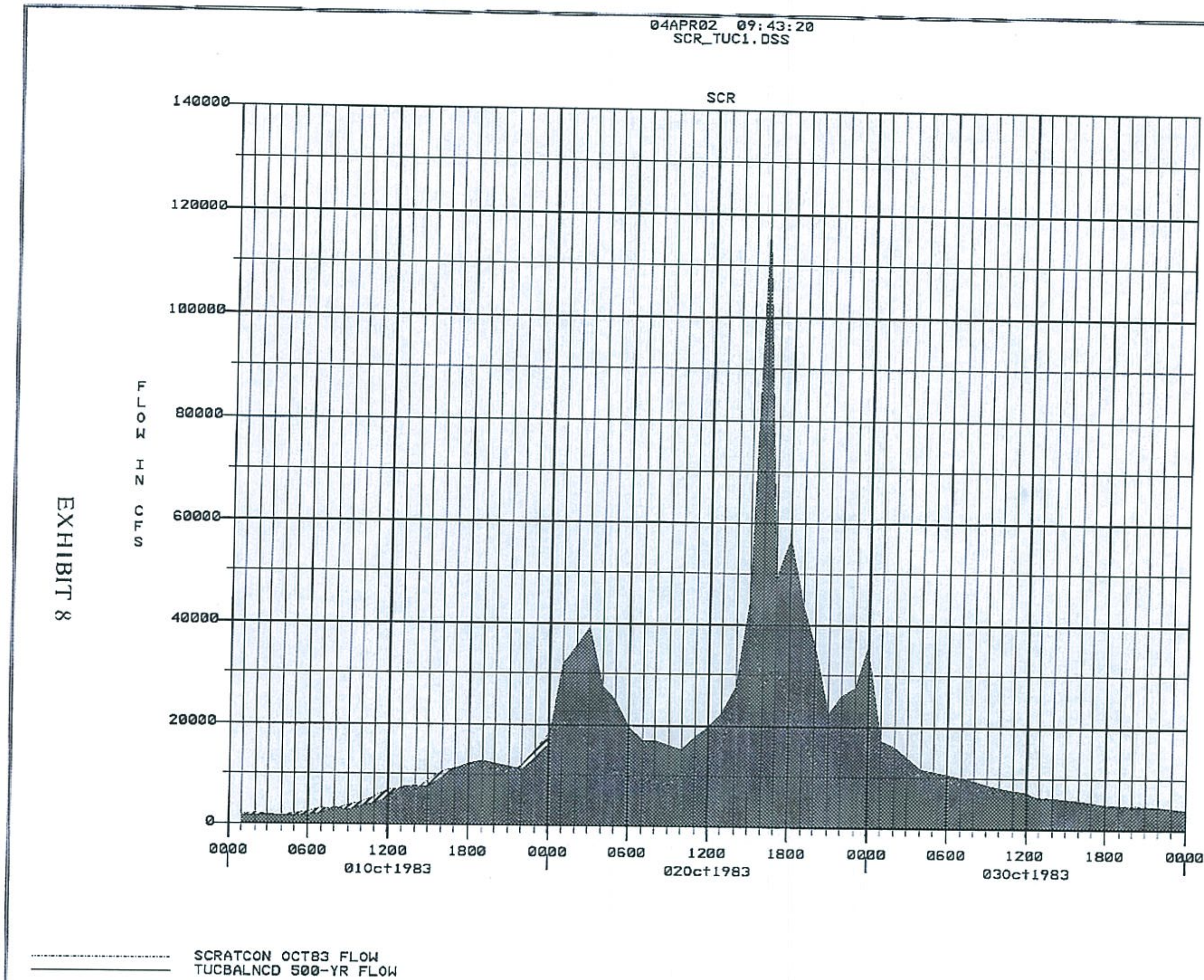
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01Oct1983
02Oct1983
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SCRATCON OCT83 FLOW
TUCBALNCD 500-YR FLOW

EXHIBIT 8